CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

BACHELOR THESIS

2019

VERONIKA ZELENÁ

Czech technical university in Prague

Faculty of Mechanical Engineering

12120 Department of Automotive, Combustion Engine and Railway Engineering

BACHELOR THESIS

Advanced Valve Actuation of a Diesel Engine with respect to Aftertreatment Systems

Pokročilé ovládání ventilů vznětového motoru s ohledem na emisní systémy

Author:	Veronika Zelená
Department:	without department
Supervisor:	Ing. Ondřej Bolehovský
	Ing. Zuzana Brejníková

Prague 2019

ČVUT
ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: **Zelená** Jméno: **Veronika** Osobní číslo: **466636**

Fakulta/ústav: **Fakulta strojní**

Zadávající katedra/ústav: **Ústav automobilů, spalovacích motorů a kolejových vozidel**

Studijní program: **Teoretický základ strojního inženýrství**

Studijní obor: **bez oboru**

II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce:

Pokročilé ovládání ventilů vznětového motoru s ohledem na emisní systémy

Název bakalářské práce anglicky:

Advanced Valve Actuation of a Diesel Engine with respect to Aftertreatment Systems

Pokyny pro vypracování:

Proveďte rešerši ohledně možností, které přináší pokročilé ovládání ventilů u vznětových motorů, se zvláštním zaměřením na vliv na emisní systémy.
Seznamte se s výpočetním softwarem GT-Power.
Na dodaném modelu vznětového motoru v GT-Power proveďte analýzu vybraných přístupů pokročilého ovládání ventilů a jeho vliv na ohřev zjednodušeného modelu emisních systémů.

Seznam doporučené literatury:

SAE Technical Paper Database
Macek, J. Spalovací motory 1, Praha, ČVUT, 2007
GT-SUITE Manuals

Jméno a pracoviště vedoucí(ho) bakalářské práce:

Ing. Ondřej Bolehovský, ústav automobilů, spalovacích motorů a kolejových vozidel FS

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) bakalářské práce:

Datum zadání bakalářské práce: **18.04.2019** Termín odevzdání bakalářské práce: **10.07.2019**

Platnost zadání bakalářské práce: ____________

Bolehovský
Ing. Ondřej Bolehovský
podpis vedoucí(ho) práce

doc. Ing. Oldřich Vítek, Ph.D.
podpis vedoucí(ho) ústavu/katedry

prof. Ing. Michael Valášek, DrSc.
podpis děkana(ky)

III. PŘEVZETÍ ZADÁNÍ

Studentka bere na vědomí, že je povinna vypracovat bakalářskou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací.
Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v bakalářské práci.

29.4.2019
Datum převzetí zadání

Zelená
Podpis studentky

Declaration

I, Veronika Zelená, hereby declare that this bachelor's thesis was composed by me and that work contained herein is my own. I have not used any sources other than those listed in the references.

Prague 1.6.2019 ....

Veronika Zelená

Acknowledgements

First, I would like to thank Eaton European Innovation Center in Roztoky for giving me an opportunity to do my research study with the organization. I am grateful to Ing. Ondřej Bolehovský for his guidance and for his support with GT-SUITE. I am also thankful to all my colleagues, especially to Ing. Zuzana Brejníková for her necessary consultations.

Last but not least, I would like to thank to my parents and friends for all the love and support.

Contents

Annotation

Key words: Diesel engine, Diesel Oxidation Catalyst, Diesel particulate filter, variable valve timing, emissions, GT-SUITE, European emissions standards

Annotation:

This bachelor thesis deals with aftertreatment heat-up. The target of this thesis is to research the engine emissions, parts of aftertreatment in diesel engine, European emission standards and variable valve timing, particulate early exhaust valve opening (EEVO) and negative valve overlap (NVO). The valvetrain is the full variable. The second part of this thesis deals with steady-state and transient-state simulations in the software GT-SUITE. At the end of this thesis, I will suggest the most efficient strategy for aftertreatment heat-up.

Anotace

Klíčová slova: naftový motor, oxidační katalyzátor, filtr pevných částic, variabilní ventilový rozvod, emise, GT-SUITE, evropská legislativa Euro

Anotace:

Práce se zabývá ohřevem systému zpracování spalin naftového motoru. Cílem této práce je provést rešerši na emise, části výfukového systému na zpracování spalin v naftovém motoru, evropskou legislativu a na variabilní ventilové rozvody, konkrétně dřívější otevření výfukového ventilu a negativní překrytí zdvihových křivek výfukového a sacího ventilu. Ventilový rozvod je plně variabilní. Druhá část této práce se zabývá ustálenými a přechodovými ději, které jsou simulovány v programu GT-SUITE. V závěru této práce je na základě provedených simulací vybrána strategie, která nejlépe ohřeje výfukový systém na zpracování spalin.

Definitions/Abbreviations

BSFC – Brake specific fuel consumption

CA – Crank angle

DOC – Diesel oxidation catalyst

DPF – Diesel particulate filter

EEVO – Early exhaust valve opening

EGR – Exhaust gas recirculation

EUDC – Extra urban driving cycle

EVC – Exhaust valve closing

EVO – Exhaust valve opening

iEGR – Internal exhaust gas recirculation

IVC – Intake valve closing

IVO – Intake valve opening

NEDC – New European Driving Cycle

NVO – Negative valve overlap

RDE – Real driving emissions

SCR – Selective catalytic reduction

SOC – Start of combustion

UDC – Urban driving cycle

VGT – Variable geometry turbine

WLTC – Worldwide harmonize Light vehicle Cycle

WLTP – Worldwide harmonized Light vehicle Test Production

$(NH_2)_2CO$ – Urea

C_3H_6 –Propylene

CO – Carbon monoxide

CO_2 – Carbon dioxide

H_2O – Water

HC - Hydrocarbons

HNCO – Isocyanic acid

N_2 – Nitrogen

N_2O –Nitrous oxide

NH_3 – Ammonia

NO – Nitrogen oxide

NO_2 – Nitrogen dioxide

NOx – Nitrogen oxides

O_2 – Oxygen

PM – Particulate matters

SiO_2 – Silicon dioxide

SiO_3 – Silicate

UHC – Unburned hydrocarbons

$\dot{m}$ [kg.s^{-1}] – boundary mass flux into volume, $\dot{m} = \rho A u$

m [kg] – mass of the volume

V [m^3] – volume

p [Pa] – pressure

ρ [kg.m^{-3}] – density

A [m^2] – cross-sectional flow area

A_s [m^2] – heat transfer surface area

e [J.kg^{-1}] – total specific internal energy (internal energy plus kinetic energy per unis mass)

H [J.kg^{-1}] – total specific enthalpy

h [W.m^{-2}.K^{-1}] – heat transfer coefficient

T_{fluid} [K] – fluid temperature

T_{wall} [K] – wall temperature

u [m.s^{-1}] – velocity at the boundary

C_f [1] – Fanning friction factor

C_p [1] – pressure loss coefficient

D [m] – equivalent diameter

r [g.s^{-1}] – fuel consumption rate

P [W] – power

List of Figures

List of tables

1. Introduction

The limits for diesel engine emissions have been significantly reduced in the last several years by European emissions legislation. Vehicle emissions have a negative impact on human health and the environment. Cars, trains and other engine-driven vehicles produce harmful pollution. There must be an effort to decrease the number of these harmful particles. It has created the need for better fuel economy and a cleaner atmosphere. This requires manufactures to develop new technologies to reduce dangerous pollution, including oxides of nitrogen (NOx), particulate matters (PM) and unburned hydrocarbon (UHC), from being released into the atmosphere. However, there are other pollutants being regulated as well, but they are not such a problem. Nowadays we follow the norm EURO 6, which is divided into two main parts according to the different technologies of gasoline and diesel engines. From September 2018 limits for oxide of nitrogen have been made stricter.

Manufacturers invest a lot of effort into continuously developing new technologies of aftertreatment systems to meet the European emission standards. To achieve these limits, the valve timing can be changed for producing lower amount of raw emissions or an aftertreatment can be built. There is the possibility to combine both strategies in a single car. If lower raw emissions are demanded, exhaust gas recirculation (EGR) can be used. EGR works on principle of returning exhaust gases back into the cylinder, thus decreasing the amount oxides of nitrogen in the exhaust. Both gasoline and diesel engines mostly use different aftertreatment systems. Gasoline engines typically incorporate the three-way catalyst, while in diesel engines the exhaust aftertreatment system consists of the diesel oxidation catalyst (DOC), diesel particulate filter (DPF) and selective catalyst reduction (SCR) systems. The DOC transforms unburned hydrocarbon (UHC) into carbon dioxide (CO_2) and water (H_2O), as well as nitrogen oxides (NOx) into nitrogen (N_2). The DPF catches PM. The SCR system reduces NOx to N_2 and water. Temperature plays an important role here. Each device starts working efficiently at a different temperature. The faster the devices heat-up, the sooner the devices work productively.

One way on how to find the amount of harmful pollution emitted is done by testing the driving cycle. There are two kinds of tests, the New European driving cycle (NEDC) and the Worldwide harmonized light vehicle test production (WLTP). The WLTP test is a more dynamic process than NEDC because of more acceleration periods and less idling time. The testing time is longer and the amount of harmful pollution released corresponds to the measured values in laboratory.

The thesis will focus on a two-liter diesel engine simulation with a variable valve actuation, such as an early exhaust valve opening and a negative valve overlap. The target of this bachelor thesis will be to simulate variable valve actuations for steady state and transient state using the software GT-SUITE.

2. Emission

Air is a vital part of our lives. In fact, it is essential to all life on earth. Air is composed of 78 % nitrogen, 21 % oxygen and 1 % of other elements, in which harmful pollutants such as nitrogen oxides (NOx), carbon dioxide (CO_2), carbon oxide (CO), particulate matter (PM), unburned hydrocarbons (UHC), etc. can be present. These pollutants have adverse effects on humans and the planet, as a whole. These harmful emissions impact the earth greatly, for example by causing acid rain and, worst of all, participating in the green-house effect which ultimately leads to global warming. Humans are constantly exposed to them through breathing as well as absorbing them through the skin. It is dangerous for people, especially when the concentration is high. They can cause a decrease in attention, tiredness and headaches when the pollutants are too many (for example in building, where there is not adequate air-conditioning). The ultimate purpose in continuously developing new aftertreatments is to limit the release of these harmful pollutants..

In this chapter, pollutants which are present in the exhaust gases of diesel engines, such as NOx, CO_2, CO, PM and UHC, will be described separately. The sub chapters will focus on their formation, properties and effect on human health.

2.1. Oxides of nitrogen NOx

Oxides of nitrogen can be a colourless to brownish gas with a harsh, sweet smell. They represent a group of nitrogen compounds, composed of nitrogen oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O). Nitrogen oxides are a natural part of environment. In nature, microorganisms and thunderstorms can produce natural oxides of nitrogen. In engines NOx can originate from very high temperatures of over 1,500 °C. [1], [10]

2.2. Particulate matter PM

Particulate matter is very small. It can consist of particles smaller than 10nm. PM is a mixture mainly of soot and inorganic matter from burned fuel and oil. There is a higher possibility of the occurrence of PM in engines with direct injection. It is produced through short burning time and the incomplete mixing of the solution. Thus, the ratio of particulate matter in exhaust gases from indirect injection is negligible compared to those from direct injection engines. [1], [10]

2.3. Carbon monoxide CO

Carbon monoxide is a toxic, tasteless, colourless and odourless gas. It is slightly lighter than oxygen. For humans it is dangerous because it blocks the transport of oxygen in the blood. At higher concentration, it can even cause death. Carbon monoxide is a product of incomplete combustion. [1], [10]

2.4. Carbon dioxide CO_2

Carbon dioxide is all around us. It is one of the products of cellular respiration. In engines, carbon dioxide is a product of complete combustion. CO_2 is a tasteless, colourless and odourless gas. It is heavier than oxygen. It contributes to the global warming process. Carbon dioxide supports the activity of carbon monoxide. It has been shown in many studies to cause headaches, sweating, and even unconsciousness after a few minutes when humans are exposed to higher concentrations. [1], [10]

2.5. Unburned hydrocarbon UHC

Diesel fuels are composed mainly of carbon and hydrogen, whose compounds are hydrocarbons (HC). Hydrocarbons are large complicated molecules made up of alkanes, alkenes, aldehyde, etc. When the amount of oxygen in a combustion chamber is higher, the complicated molecules of HC are reduced. The HC which are not burned are called unburned hydrocarbons (UHC). The reasons UHC form are due to low temperature

near a colder surface such as a cylinder wall or an oil leak in the piston rings. UHC can also develop from an uneven process of combustion or a low burning temperature. [1], [10]

3. The aftertreatment system

The aftertreatment system in diesel engines typically consists of these components: oxidation catalyst, a device to reduce NOx and a device to catch PM. For the reduction of raw emissions we use exhaust gas recirculation (EGR). In this chapter the components of aftertreatment such as the diesel oxidation catalyst, diesel particulate filter, exhaust gas recirculation and selective catalytic reduction will be described. The following sub-chapter will be focused on temperature, material, efficiency and other important abilities of their functionality.

3.1. Diesel oxidation catalyst DOC

The diesel oxidation catalyst is the catalyst for oxidation reaction. It is capable of oxidizing HC and CO emissions. Its secondary catalyst activity is oxidizing NO to NO_2. The compounds in DOC are transformed according to following equations. [5]

$$CO + \frac{1}{2}O_2 \rightarrow CO_2$$

Equation 1

$$C_3H_6 + \frac{9}{2}O_2 \rightarrow 3CO_2 + 3H_2O$$

Equation 2

$$NO + \frac{1}{2}O_2 \rightarrow NO_2$$

Equation 3

*"CO and HC are oxidized to form CO_2 and H_2O (*Equation 1 *and* Equation 2*) in the DOC". [5]* The oxygen (O_2) that is present in these reactions is not the same oxygen as the oxygen which reacts with the fuel in the combustion chamber. Accordingly, the oxygen in these reactions is aspirating from outside the car. [5]

To meet the most efficient state of DOC, the DOC has to reach a higher temperature than the so-called "light-off" temperature. The light-off temperature indicates the start of the reactions in the catalyst. Many catalysts start efficiently working at 200 °C, which is their light-off temperature. [5]

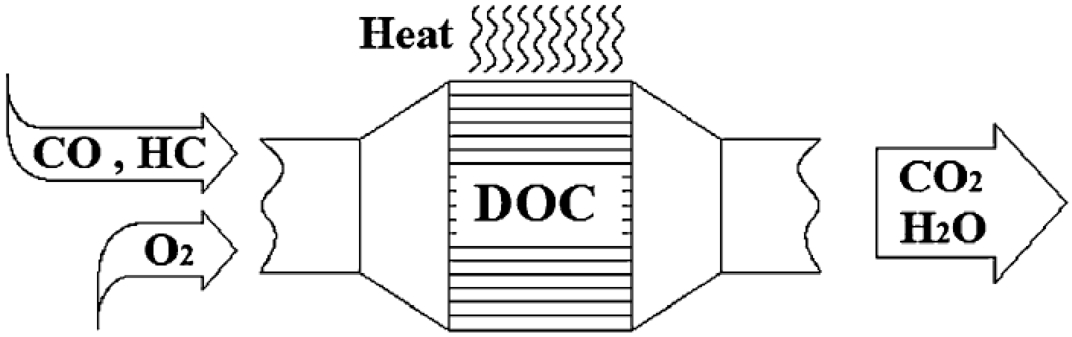


Figure 1 - Diesel oxidation catalyst [5]

Figure 1 shows the schematic organization of the diesel oxidation catalyst. As we can see in Figure 1, there is heat escaping from the catalyst. This heat is the product of the chemical reaction and is helpful in the warm-up of the next aftertreatment device behind the DOC. [5]

The DOC is capable of transforming silicon dioxide (SiO_2) into silicate (SiO_3). When SiO_3 and water react, it causes sulphuric acid or other forms of sulphate. Unfortunately, these sulphur compounds have damaging impact on the aftertreatment control systems. They can cause environmental and health issues as well. Unlike other pollutants, there does not exist any technology to catch these forms. On the other hand, when alternative fuels (such as biodiesel, methyl alcohol, etc.) are used, sulphur compounds are reduced. European standards are higher, therefore Europe has lower sulpher in the air than other regions. [5]

3.2. Diesel particulate filter DPF

The diesel particulate filter is a filter made of porous material which has the ability to catch PM. This porous structure is built from multiple parallel channels, typically in a square shape (Figure 2). PM, which are commonly between 2.5 – 10 micrometres, can travel through these channels because the dimension of channels' walls are 300 – 400 micrometres. PM are able to adhere the inside walls. PM are transported by diffusion inside the walls. When the filter is almost full, there is a difference in pressure before and after the filter. The saturation is obvious when the filter builds up backpressure which causes higher consumption, stress in the filter and, even, engine failure. To prevent these situations, the filter has to undergo regeneration. There are two types of regeneration: active and passive regeneration. In both forms of regeneration the adhered PM are burned. [1], [3], [5]

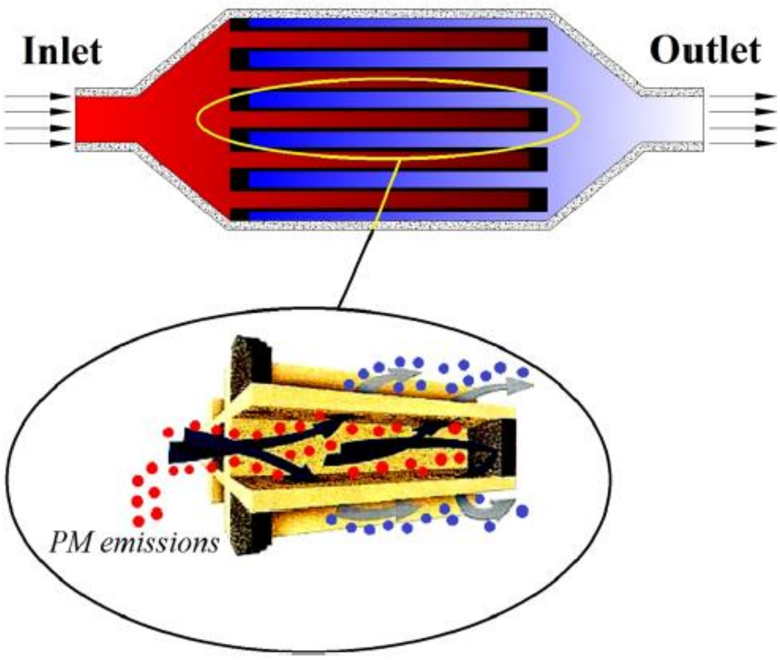


Figure 2 - DPF filtration [5]

Passive regeneration is caused by the engine's exhaust heat in normal operation. Active regeneration introduces very high heat into the exhaust system. It is caused by injecting more fuel during engine operation or by injecting fuel into the exhaust manifold. [5]

3.3. Exhaust gas recirculation EGR

Exhaust gas recirculation works on the principle of returning exhaust gases back to cylinder. In the cylinder, fuel and fresh air are mixed with the exhaust gases, which act as an inert gas and is cooled before entering the cylinder. Low combustion temperature means lower thermal efficiency of the cycle which, in turn, means higher fuel consumption. EGR commonly works, when the engine is heated on operating temperature. The recirculation is controlled by temperature, speed and load. Figure 3 shows the schematic EGR within the engine. [5]

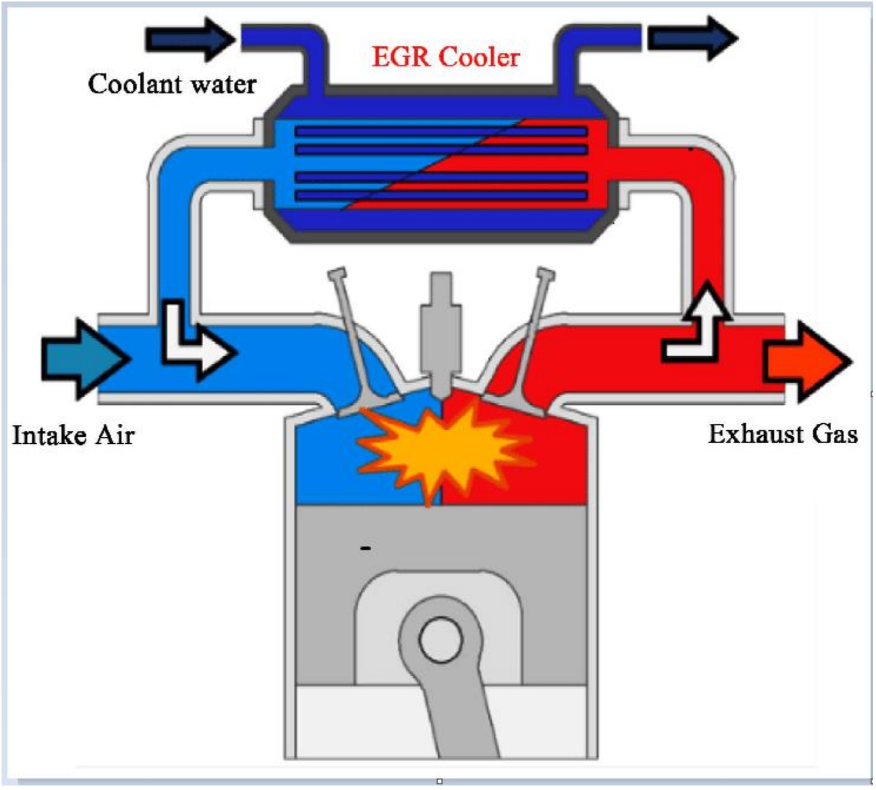


Figure 3 - Schematic EGR [12]

EGR can be divided into two groups: internal and external. Internal EGR (iEGR) uses an advanced valve train system. There are two external EGR types: high pressure and low pressure. The high pressure EGR is attached between two high pressure components. The manifold of the high pressure EGR is connected to the pipeline going from the compressor to the turbine. Low pressure EGR re-circulates exhaust gas from the exhaust system tail pipe and it is attached to the compressor inlet. Figure 4 and Figure 5 shows high pressure system EGR and low system EGR. [5], [11]

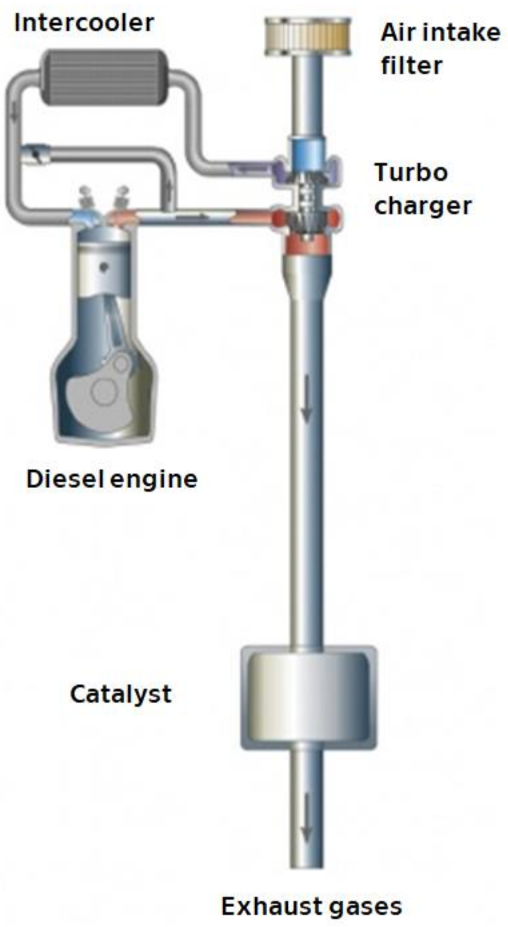


Figure 4 - High pressure EGR [11]

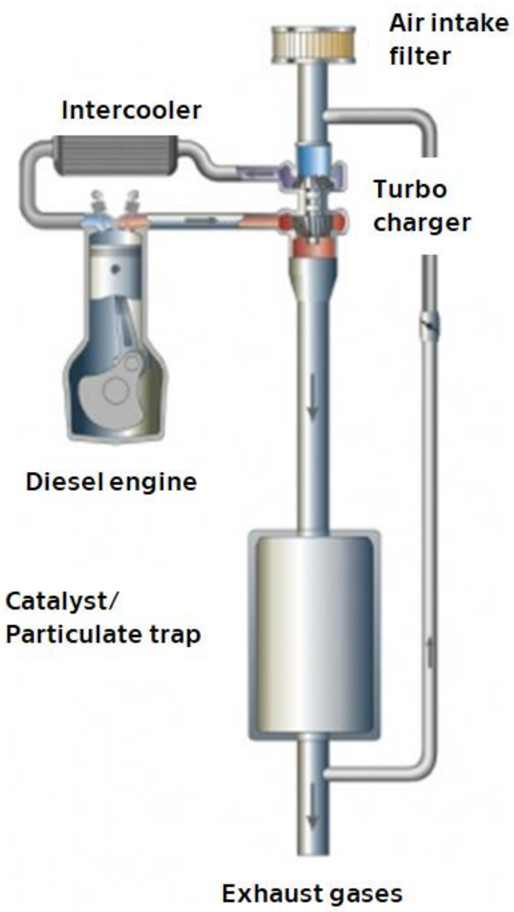


Figure 5 - Low pressure EGR [11]

3.4. Selective catalytic reduction SCR

SCR is another device used to reduce NOx from exhaust gas. SCR needs special liquid for the degeneration of nitrogen oxide. This special liquid is a mixture of 33% urea (chemical formula: $(NH_2)_2CO$) and 67% water. The most efficient liquid on the market worldwide is known as AdBlue. The AdBlue system consists of a special tank and pipelines. [5]

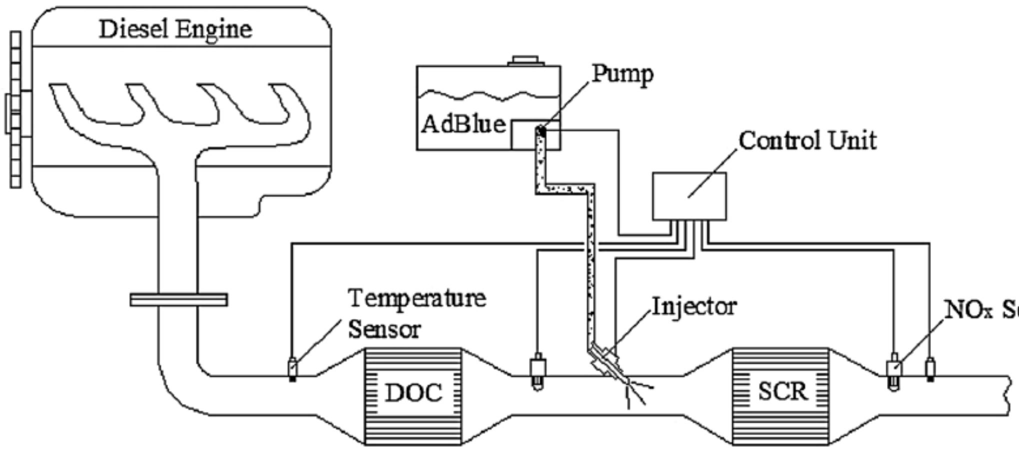


Figure 6 - SCR system [5]

AdBlue is injected before SCR, as we can see in Figure 6. Thermolysis converts AdBlue into ammonia (NH_3) and isocyanic acid (Eq. 4). Then the isocyanic acid reacts with the water, which is contained in AdBlue, by hydrolysis. The products of hydrolysis are ammonia and carbon dioxide (Equation 5). [5]

$$(NH_2)_2CO \rightarrow NH_3 + HNCO$$

Equation 4

$$HNCO + H_2O \rightarrow NH_3 + CO_2$$

Equation 5

The reaction time between thermolysis and hydrolysis is shorter than time of the SCR reaction, so the ammonia can originate. NH_3 becomes a reactant once entering the SCR. These chemical reactions, which are shown below, are in progress in SCR. [5]

$$4\,NO + 4\,NH_3 + O_2 \rightarrow 4\,N_2 + 6\,H_2O$$

Equation 6

$$2\,NO + 2\,NO_2 + 4NH_3 \rightarrow 4N_2 + 6\,H_2O$$

Equation 7

$$6\,NO_2 + 8\,NH_3 \rightarrow 7\,N_2 + 12\,H_2O$$

Equation 8

"The rate of reaction in Equation 7 is higher than the other reactions." [5] There is an external source of oxygen before SCR. [5]

AdBlue is injected into pipeline when the wall temperature reaches over 200 °C. If AdBlue is injected under 200 °C, it causes the formation of toxic acids. The temperature should not be higher than the melting point of the SCR material, thus, the optimum temperature is around 350 °C. [5]

4. Legislation

4.1. European emission standards

All vehicles powered by combustion engines are a source of pollutants. The purpose of imposing emission standards is to decrease the release of dangerous pollutants in the atmosphere. They are harmful to people and planet as well. Every country has their own legislation for passenger vehicles, airplanes, shipping and other engine vehicles. The Czech Republic follows the European Union emissions standards, called Euro emissions limits. Euro emissions limits started in 1992. Since that year, the acceptable amount of pollution allowed continuously decreases. As it shows in Table 1, the acceptable amount of CO, NOx, HC + NOx and PM in Euro 6 are lower than in Euro 1. [13]

Limit	Effective	CO [g/km]	NOx [g/km]	HC+NOx [g/km]	PM [mg/km]
Euro1	1992	2,72	-	0,97	140
Euro2	1996	1,0	-	0,7	80
Euro3	2000	0,64	0,5	0,56	50
Euro4	2005	0,5	0,25	0,3	25
Euro5	2009	0,5	0,18	0,23	5
Euro6c	Sep 2018	0,5	0,08	0,17	4,5
Euro6d	Jan 2021	0,5	0,08	0,17	4,5
Euro6d-Temp	Sep 2019	0,5	0,08	0,17	4,5

Table 1 - EU EMISSION STANDARDS FOR PASSENGER CARS [13]

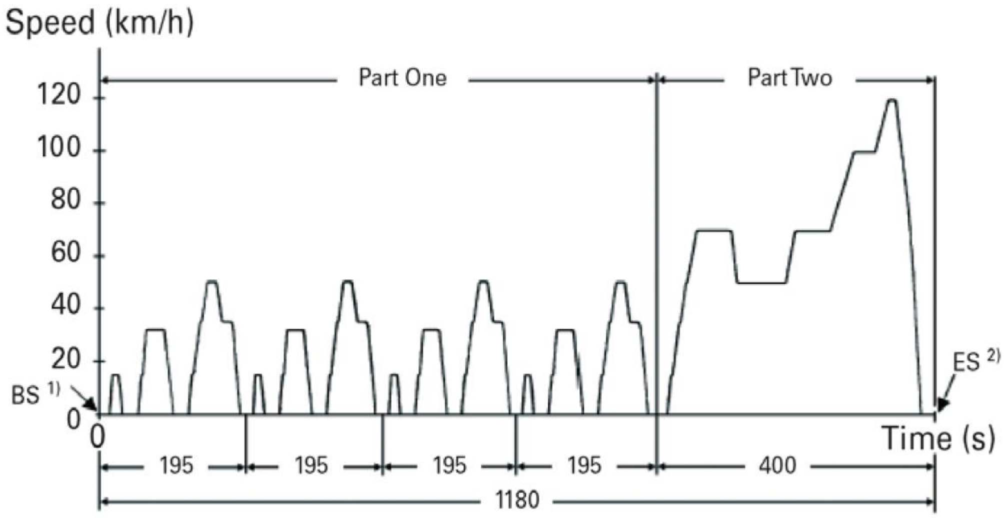
Emissions were originally tested by urban driving cycle (UDC), extra urban driving cycle (EUDC), new European driving emission (NEDC). Emissions are now tested by worldwide harmonized Light vehicle Test Production (WLTP) and real driving emissions (RDE). For more information about testing cycle look in Delphi Technologies book [13]. [13]

Euro1 and Euro2 did not differenciate between HC and NOx emission. They measured them together in one sum. From Euro3, the limit of NOx and HC is analyzed separately. The accepted NOx emission limit between Euro5 and Euro6c is enormous, from 0,18 g/km to 0,08 g/km. Euro6 is divided into a number of sub-groups because the standard has not changed, but the measuring method has. Euro6c is the standard for WLTP measurements. Euro 6d-Temp and Euro 6d are the standards for RDE measurements. For more information see [13]. [13]

Euro6 is not the last standard. Euro7 is being prepared, but the exact year of its publication has yet to be established.

4.2. NEDC

For the measurement of emissions a driving cycle test was developed. The test is called the New European Driving Cycle NEDC, which is shown in Figure 7. Every vehicle has to pass this test. Vehicles can be compared based on the test results. The driving test is divided into two groups: urban and extra-urban cycle. The graph below shows the duration of cycle. The test starts with a cold vehicle. The test profile is consists of idling, soft acceleration and low speed. This is a standard benchmark test, but it does not correspond with real driving, so it was decided to create a new test for more realistic emission production analysis. [13]



1) BS: Beginning of Sampling at engine start.
2) ES: End of Sampling.

Figure 7 - NEDC [13]

4.3. WLTC

The worldwide harmonized light vehicle cycle (Figure 8) is a part of the worldwide harmonized light vehicles test production. It was introduced in Europe in September 2017 and was fully implemented starting from September 2018 for all vehicles. In comparison with NEDC, the WLTC has faster acceleration and a shorter idling period. The first part simultates driving in the city. The velocity is not higher than 60 kph. The second part displays driving in the city with increased velocity. The third part describes driving outside the city (intercity). The last part shows driving on the highway. This cycle corresponds to more realistic driving. [13]

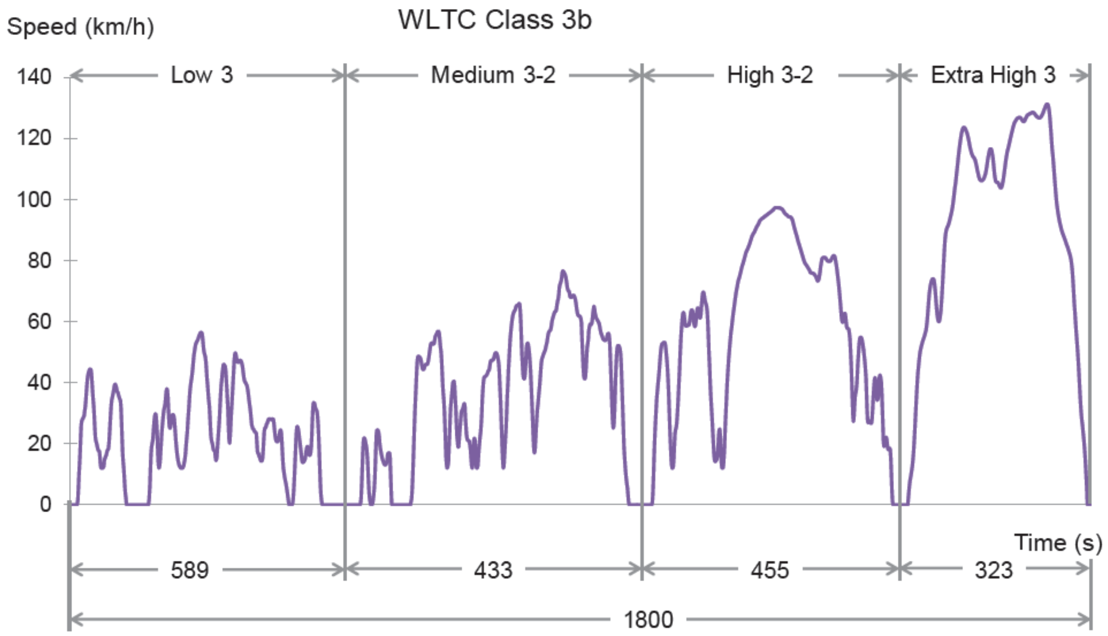


Figure 8 - WLTC cycle [13]

4.4. Comparing NEDC and WLTC

The comparison of both cycles - NEDC and WLTP - is shown in Table 2. WLTP has longer distance, cycle duration, average speed and maximum speed. It also requires a higher consumption of fuel.

	NEDC	WLTC
Duration of cycle [sec]	1 180	1 800
Length of cycle [km]	11.03	23.27
Average speed [kph]	33.60	46.50
Maximum speed [kph]	120.00	131.30
Neutral share [%]	23.70	12.60
Constant drive share [%]	40.30	3.70
Acceleration share [%]	20.90	43.80
Deceleration share [%]	15.10	39.90

Table 2 - COMPARING NEDC AND WLTC [3]

5. The variable valve actuation

This chapter will describe the strategies which help to heat up the aftertreatment. The aftertreatment could be heated up by hot exhaust gases or externally with the help of an added heater to heat up the components of aftertreatment such as diesel oxidation catalyst (DOC), diesel particulate filter (DPF) and selective catalyst reduction (SCR). This thesis will only focus on the heat-up from hot exhaust gases.

The aim of this thesis is to choose the most efficient strategy for aftertreatment heat-up with the lowest fuel consumption. Different operation points were simulated which varied in load level and valve timing.

The strategies which are able to heat-up the exhaust gases can be divided into two groups. The first group is focused on valve timing. Early exhaust valve opening (EEVO), negative valve overlap (NVO), integral exhaust gas recirculation (iEGR) belong to this group. The second group is based on the later start of combustion (SOC). In diesel engines the fuel is injected into cylinder later, while in gasoline engines the mixture is ignited later. This thesis will only focus on the timing strategies, especially of EEVO and NVO, because it is primarily interested in the exhaust-gas aftertreament heat-up.

5.1. Early exhaust valve opening EEVO

EEVO means that exhaust valve opens earlier. The maximum lift is not changed. The exhaust valve closing (EVC) is at the same time, but the exhaust valve opening (EVO) is varied.

The exhaust valve opens during the expansion stroke. The hot gases expand during the expansion stroke and, therefore, are cooled. When the exhaust valve opens before the expansion is finished, the expansion stroke is shorter and exhaust gases remain warmer. The power is eliminated but the engine should reach the requested load. The amount of fuel injected into the cylinder is higher when the requested load must be reached, despite the shorter expansion stroke.

Figure 9 shows three valve curves. The red curve represents the intake valve lift base line. The blue curve represents the exhaust valve lift base line. The blue curve starts opening at a 148 degree crank angle (CA) at 1 mm lift. The green curve represents the exhaust valve lift with EEVO strategy. The green curve starts opening at a 98 degree of CA at 1 mm lift.

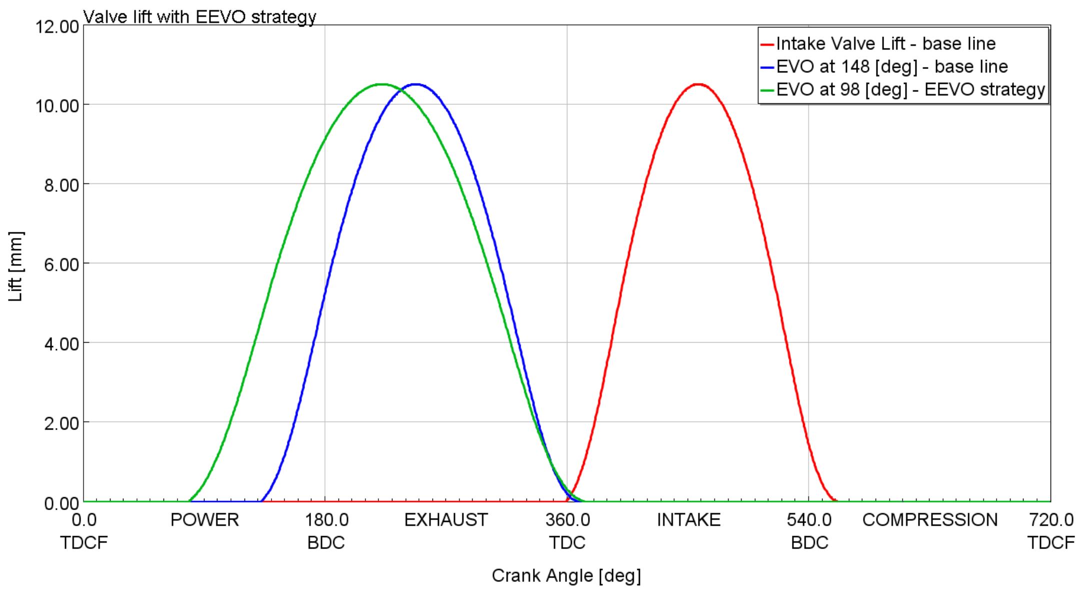


Figure 9 - Valve lift with EEVO strategy

5.2. Negative valve overlap NVO

Negative valve overlap means the exhaust and intake curves have no overlap. Negative valve overlap is represented in Figure 10 by the blue curves represent the exhaust valves close earlier and intake valves open later. The maximum lift is not changed. The exhaust valve opening (EVO) and intake valve closing (IVC) are also not changed. The exhaust valve closing (EVC) and intake valve opening (IVO) are varied. Therefore, the cylinder is not scavenged and hot exhaust gases remain inside. The burned exhaust gases fill part of the total cylinder volume, consequently leaving less space for fresh air and fuel. Since the intake stroke starts later, the cylinder is filled with less fresh air which in turn causes a lower amount of injected fuel. This process produces a lower temperature during combustion and, thus, a smaller amount of NOx emissions.

Figure 10 shows two intake valve lift curves (dashed lines) and exhaust the valve lift (full lines) curves. The red curves represent base lines with overlap. The blue curves represent NVO strategy without overlap.

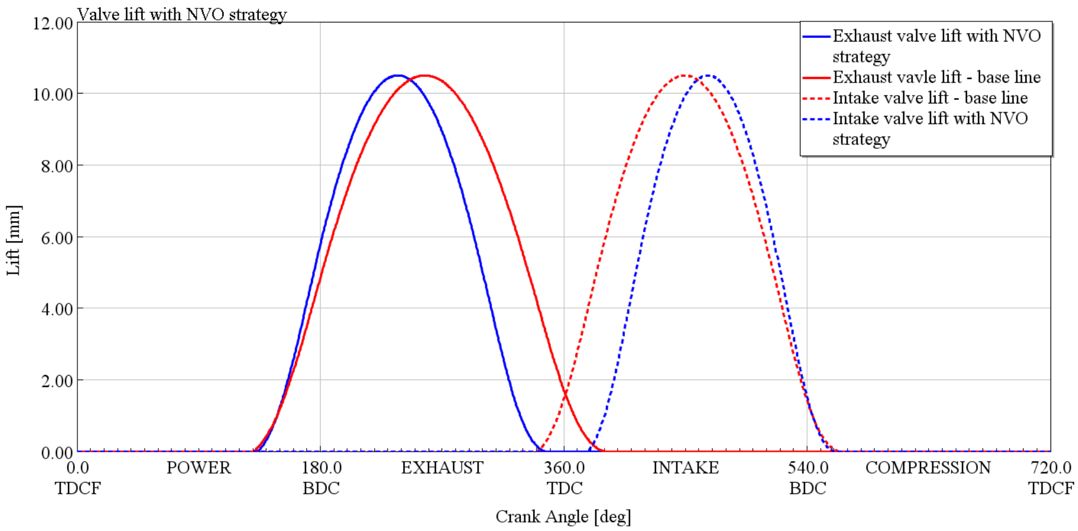


Figure 10 - Negative valve overlap

6. Simulation software

In the following section, the simulation software will be described. The main tool for simulations was GT-SUITE software. Modern companies invest an enormous amount time and money in simulations. With simulations, the parameters can be changed easier and quicker than in a real experiment in a test cell. Accurate data describing the engine (injecting strategy, combustion, dimension, temperatures, pressures, mass flows etc.) is needed to properly create a simulation. Eaton has provided the virtual model, which includes real data, for this thesis.

6.1. GT-SUITE

GT-SUITE is simulation software developed by Gamma Technologies LLC. It is used for simulations of processes in engines, powertrains and engineering simulations, such as thermal, mechanical, electrical, magnetic, chemistry and/or controls. GT-SUITE has many modules such as GEM3D, COOL3D, VTDESIGN, GT-SpaceClaim, GT-POST, and CONVERGE Lite (3D-CFD). GT-Power was used for simulations. GT-POST was used for post-processing the results from simulations. [6]

This software is capable of simulating one dimensional (1-D) and zero dimensional (0-D) objects. 1-D objects conserve fluid flow. The 1-D objects are solved by using Navier-Stokes equations; conservation of continuity (Equation 9), conservation of momentum (Equation 10) and conservation of energy (Equation 11). [6]

$$\frac{dm}{dt} = \sum_{boundaries} \dot{m}$$

Equation 9 – Conservation of continuity [6]

$$\frac{d(me)}{dt} = -p\frac{dV}{dt} + \sum_{boundaries} (\dot{m}H) - hA_s(T_{fluid} - T_{wall})$$

Equation 10 – Conservation of energy [6]

$$\frac{d\dot{m}}{dt} = \frac{dpA + \sum_{boundaries}(\dot{m}u) - 4C_f\frac{\rho u|u|}{2}\frac{dxA}{D} - C_p\left(\frac{1}{2}\rho u|u|\right)A}{dx}$$

Equation 11 – Conservation of momentum [6]

Where:

$\dot{m}$	[$kg.s^{-1}$]	– boundary mass flux into volume, $\dot{m} = \rho A u$
m	[kg]	– mass of the volume
V	[m^3]	– volume
p	[Pa]	– pressure
ρ	[$kg.m^{-3}$]	– density
A	[m^2]	– cross-sectional flow area
A_s	[m^2]	– heat transfer surface area
e	[$J.kg^{-1}$]	– total specific internal energy (internal energy plus kinetic energy per unit mass)
H	[$J.kg^{-1}$]	– total specific enthalpy
h	[$W.m^{-2}.K^{-1}$]	– heat transfer coefficient
T_{fluid}	[K]	– fluid temperature
T_{wall}	[K]	– wall temperature
u	[$m.s^{-1}$]	– velocity at the boundary
C_f	[1]	– Fanning friction factor
C_p	[1]	– pressure loss coefficient
D	[m]	– equivalent diameter

While the equations are three dimensional (3-D), we solve these equations in only one dimension; with the other two dimensions equal to zero.

The user can choose one of two options for approaching the solution differently, the explicit and implicit method. *"In the explicit method, the value of pressure, temperature, etc. at the new time is based only on the values of the subvolume in question and its neighbours. The calculation is direct and does not require iteration. The Explicit integration scheme is second-order accurate. The implicit integration scheme is also second-order accurate. The implicit integrator is recommended for stiff problems. The time step used by the implicit method is not dynamically determined* *by GT-SUITE, as in the explicit method, but is imposed by the user." [6]* More information about this problem is in GT-Power manual [6]. [6]

The second type are 0-D objects. In these objects the flow is not solved. Models of circulation have to be 3-D, which is demanding for calculation. The 3-D simulations are accurate. The 1-D simulations are simplified compared to the 3-D simulations and some phenomena are neglected. When this simplification is used, the results of these simulations approximate the accurate 3-D simulations. It is not necessary to solve the equation of conservation of momentum. It is sufficient to solve the law of conservation of energy and continuity These components are found in the cylinder, turbine or compressor. [6]

The software is able to solve both a steady state and a transient state. The transient state is period between two steady states and is used to monitor changes during this time period. The transient and steady state can give the same results if they have the same settings. Steady state simulations are used to quickly determine the result state, while the transient state is used to determine the change over time.

6.2. Description of model

The model, where the simulations were performed, is four-stroke diesel engine with a variable geometry turbine (VGT) intercooler, muffler, aftertreatment (including DOC and DPF) and EGR system. The fuel is injected directly into the cylinders. Other attributes of the model are found in Table 3. Figure 11 shows the scheme of the simulated model.

Engine Specifies	
Number of cylinders	4
Volume of cylinders [litter]	2
Stroke [mm]	86
Bore [mm]	86
Compression Ratio	17

Table 3 - Engine specifies

Figure 11 shows the simulated model in the environment of GT-SUITE.

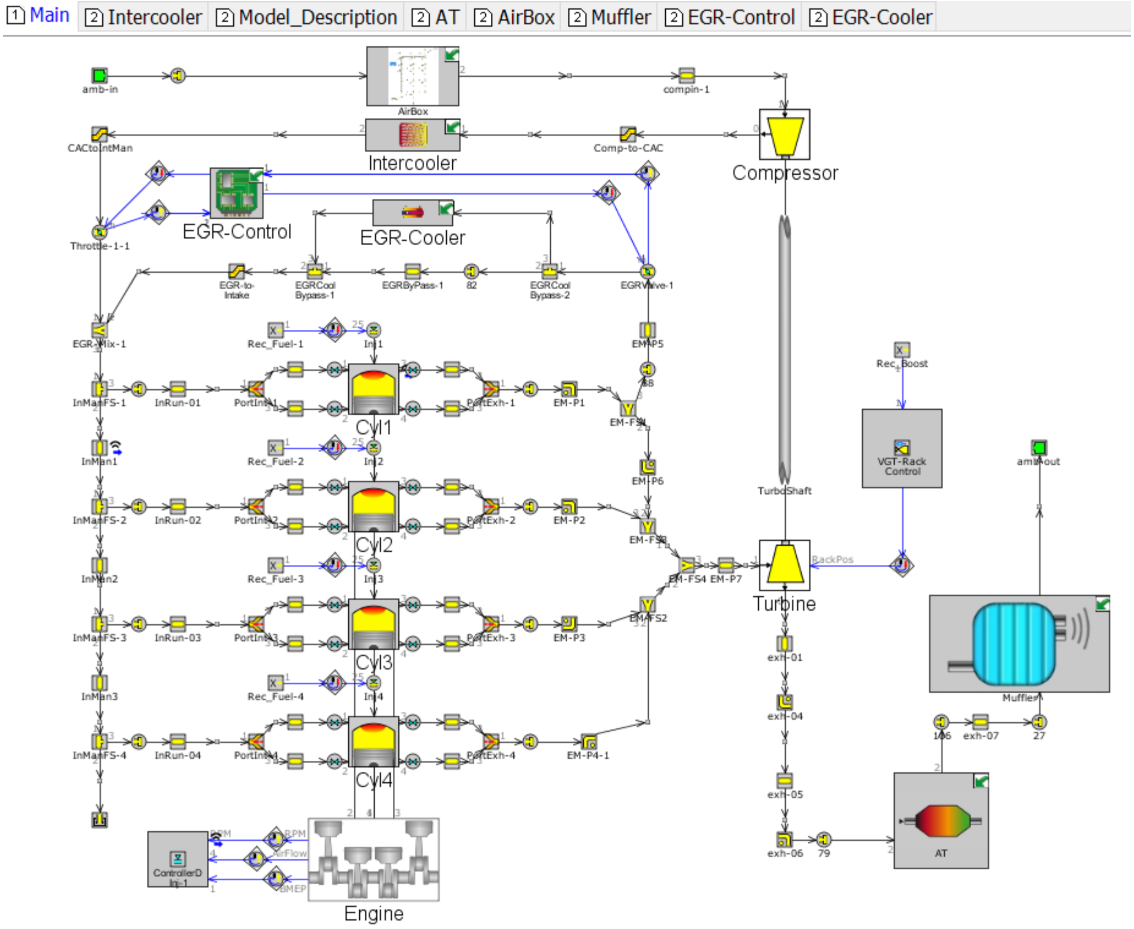


Figure 11 – The simulated model

Before the simulations began, the initial conditions had to be defined. The initial conditions, which were set for this thesis, are load level, brake mean effective pressure (BMEP), RPM and initial temperature.

The aftertreatment consists of a diesel oxidation catalyst and a diesel particulate filter. The operating point is set at 2000 RPM. A 16-bar BMEP and 6-bar BMEP load level was used. The EGR system works at only a 6-bar BMEP. When a 6-bar BMEP is used is used during the operating point, the amount of air in cylinder is higher and the amount of fuel injected into cylinder is lower. The higher amount of air causes more NOx emissions and the EGR system is able to work. When the 16-bar BMEP is used is used during the operating point, the amount of air is not much higher than the amount of fuel in the cylinder and the EGR system does not function.

The initial temperature for the transient state was defined as -7 °C, because the aftertreatment tests are done at this temperature. For more information see [13].

Table 4 shows all the conditions that were simulated.

Strategy	RPM	BMEP	EGR	State
EEVO	2000	6 bar	YES	Steady state
		6 bar	NO	Steady state
		16 bar	NO	Steady state
		6 bar	NO	Transient state
		16 bar	NO	Transient state
NVO		6 bar	YES	Steady state
		6 bar	NO	Steady state
		16 bar	NO	Steady state
		6 bar	NO	Transient state
		16 bar	NO	Transient state

Table 4 - Type of simulations

After the simulations were performed, the results were evaluated for temperature before aftertreatment and brake specific fuel consumption (BSFC) for both strategies (EEVO + NVO strategies) and burned mass percent at SOC for NVO strategy.

BSFC is defined as ratio between fuel consumption rate (r) and power (P) (Equation 12). [10]

$$BSFC = \frac{r}{P} \text{ [g/kW.h]}$$

Equation 12 – BSFC

The burned mass percentage at the SOC is defined as the ratio between the fresh mass and the burned mass in the cylinder. This value influences fuel consumption.

7. Simulation in GT-SUITE

7.1. Steady state - early exhaust valve opening EEVO

The operating point for the EEVO strategy in the model was set on 2000 RPM. The model was simulated with 16-bar and 6-bar BMEP. The EVO and EVC timings were varied. The maximum lift was not changed.

Figure 12 shows all the EEVO strategy curves. The yellow curve represents the intake valve lift – base line. The red curve represents the exhaust valve lift – base line, where the EVO starts at a 148-degree CA at 1 mm lift. The purple curve (EVO at 98 [deg]) represents the earliest time of the EVO at a 98-degree CA at 1 mm lift. If the EVO starts lower than a 98-degree CA, the engine is not able to generate enough power.

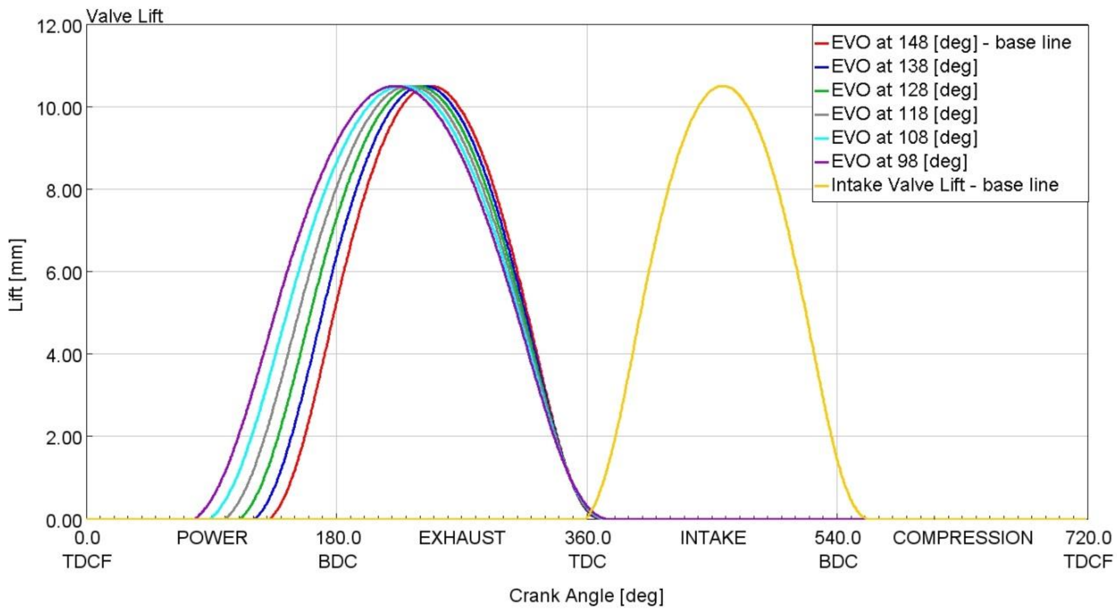


Figure 12 - EEVO - Valve lift

Figure 13 shows the influence of the EVO on the temperature. The base line point is at a 148-degree CA at 1 mm lift. The earlier the EVO starts, the higher the temperature is. The operating point of the 16-bar BMEP has a higher exhaust gas temperature than the 6-bar BMEP, with or without EGR. The EGR system usage increases the temperature. The exhaust gases travel through the EGR intercooler and then blended with the fresh mixture. These cooled exhaust gases are hotter than the fresh air. When the mixture of fresh air and fuel and warm exhaust gases are burned, the temperature in cylinder is higher.

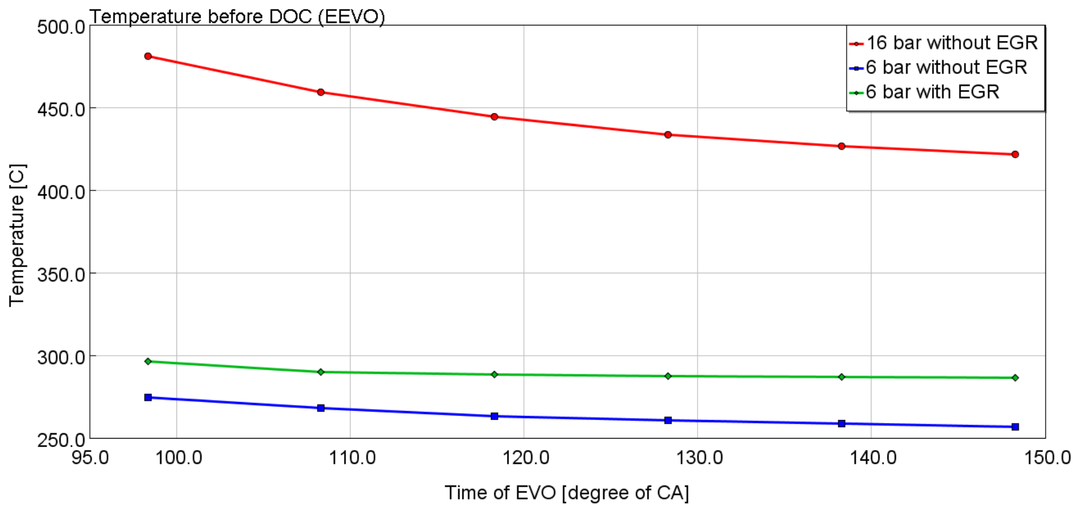


Figure 13 - Temperature before DOC (EEVO)

Table 5 shows temperature of all EEVO strategies depending on EVO time.

Temperature [°C]			
EVO at 1 mm [deg] of CA	**BMEP**		
	16 bar without EGR	6 bar without EGR	6 bar with EGR
98	481,2	274,4	296,4
108	459,0	268,0	289,7
118	444,1	263,3	288,6
128	433,6	260,5	287,4
138	426,3	258,6	286,9
148	421,7	256,6	286,2

Table 5 - Temperature before DOC (EEVO)

Figure 14 shows brake specific fuel consumption depending on the time of the EVO.

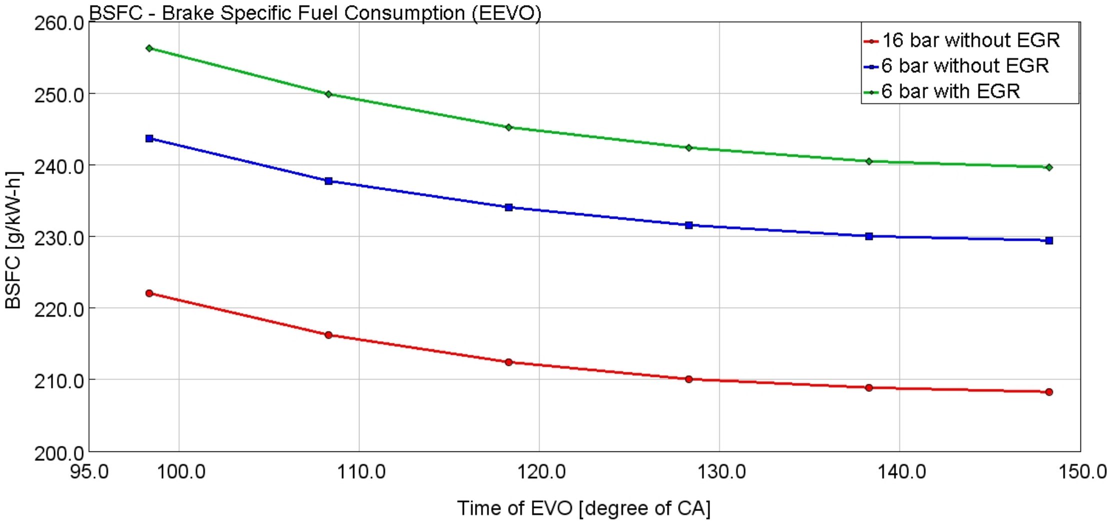


Figure 14 – BSFC (EEVO)

Table 6 shows the BSFC of all the EEVO strategies. The 16-bar BMEP has a lower fuel consumption compared with operating point of the 6-bar. When the EGR system is used, the fuel consumption is higher.

BSFC [g/kW.h]			
EVO at 1 mm [deg] of CA	**BMEP**		
	16 bar without EGR	6 bar without EGR	6 bar with EGR
98	222,0	243,6	256,3
108	216,2	237,7	249,8
118	212,4	234,0	245,2
128	210,0	231,5	242,3
138	208,8	230,0	240,5
148	208,3	229,4	240,0

Table 6 – BSFC (EEVO)

7.2. Steady state - negative valve overlap NVO

The operating point of the NVO strategy was set at 2000 RPM. The model was simulated with 16-bar BMEP and 6-bar BMEP. The EGR system works on 6-bar BMEP. Figure 16 shows all the curves which were simulated. The maximum lift was not changed. The times of EVO and IVC were not changed. The times of EVC and IVO were varied.

The following convention was used for data evaluation. When the intake and exhaust curves do not intersect, they have positive NVO (Figure 15). This indicates the number between IVO and EVC at 0 mm lift is positive (Equation 13).

$$Difference\ between\ curves = IVO - EVC$$

Equation 13

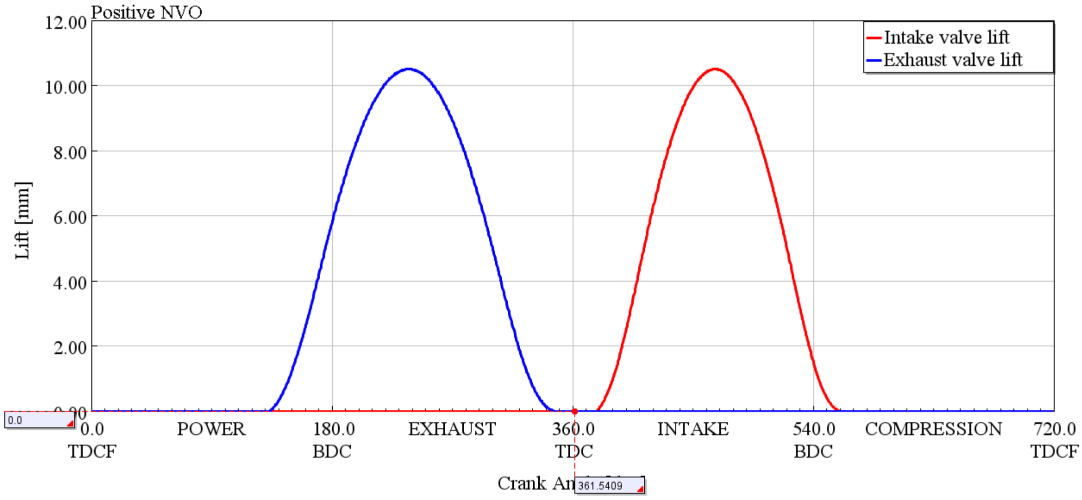


Figure 15 - Positive NVO

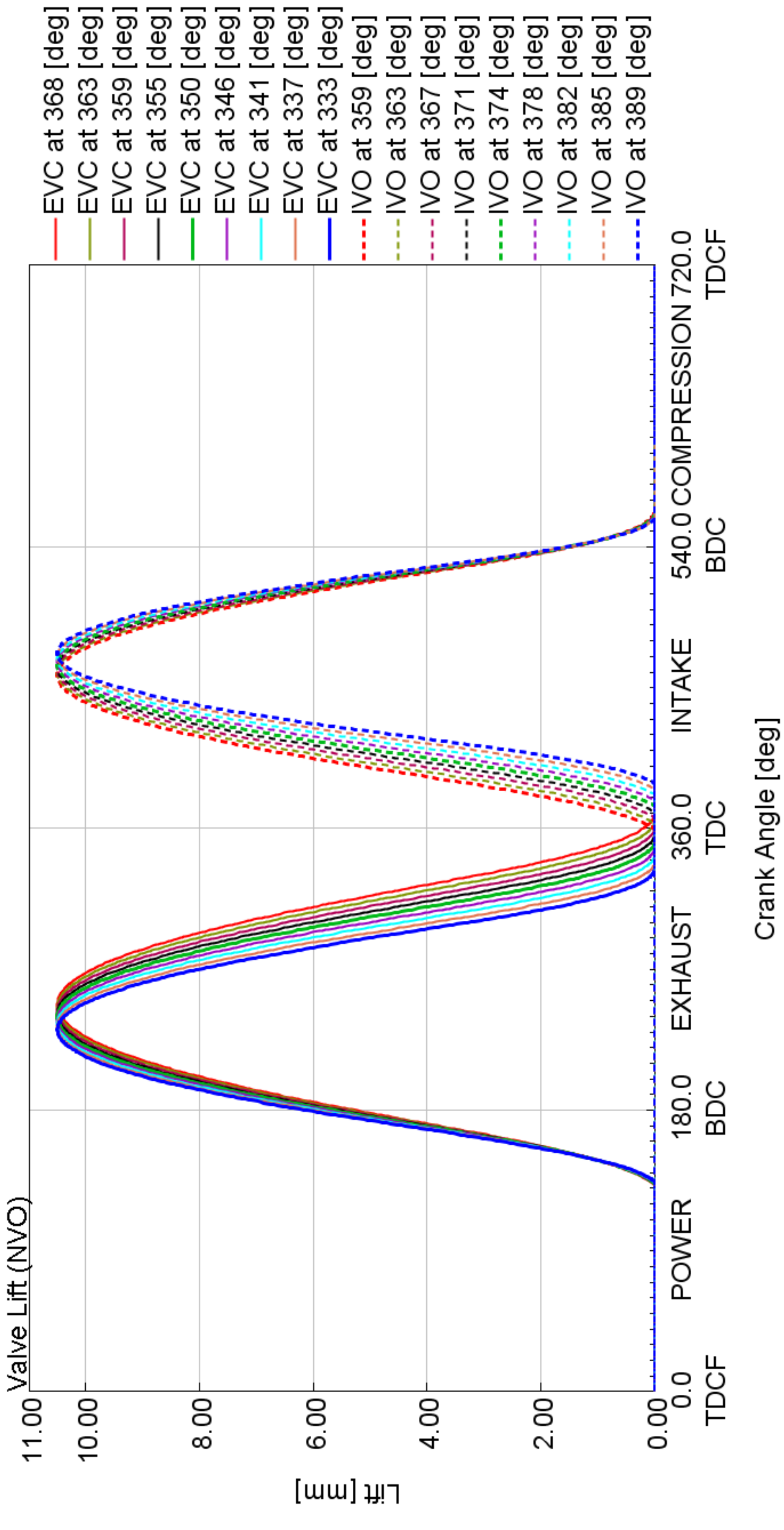


Figure 16 - Valve lift (NVO)

When the intake and exhaust curves intersect, the curves have a negative NVO (Figure 17). That means the number between IVO and EVC at 0 mm lift is negative (Equation 13). In the following tables and figures the convention of difference between EVC and IVO is called Difference between curves [degree of CA].

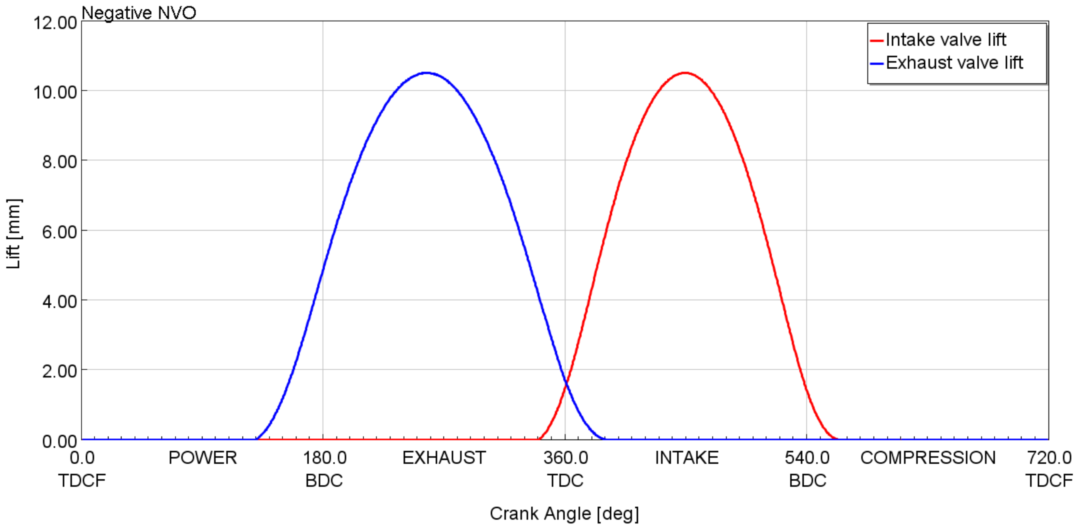


Figure 17 - Negative NVO

The evaluated results were taken from the measured temperature before the DOC, BSFC and the burned mass percentage at the start of combustion.

Figure 18 shows the temperature before the DOC of all NVO strategies. The highest temperature has the operating point of 16-bar BMEP compared with 6-bar BMEP. The higher the difference between the curves is, the higher the temperature of exhaust gases are. The difference of the base line setting is at a -8.2-degree CA at 0 mm lift.

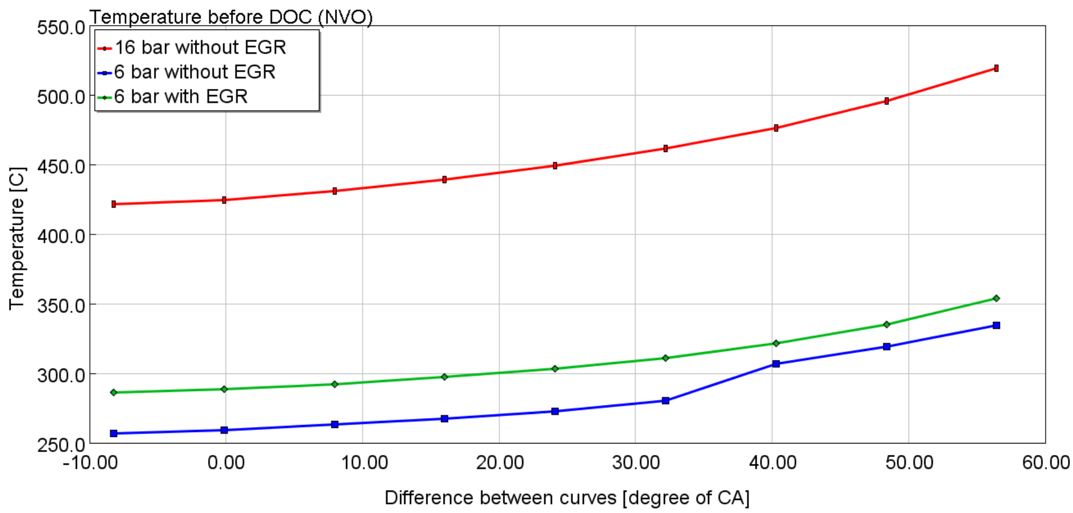


Figure 18 - Temperature before DOC (NVO)

Table 7 shows temperature of all NVO strategies before DOC.

Temperature [°C]			
IVO and EVC difference [deg] of CA	**BMEP**		
	16 bar without EGR	6 bar without EGR	6 bar with EGR
-8,2	421,8	256,8	286,4
-0,1	424,6	259,3	288,8
7,9	430,6	263,0	292,3
16,0	439,1	267,3	297,3
24,1	449,0	272,7	303,4
32,2	461,2	280,6	311,2
40,3	476,4	307,0	321,3
48,4	495,3	319,0	335,1
56,5	519,3	334,5	353,9

Table 7 - Temperature before DOC (NVO)

Figure 19 shows the BSFC of all the NVO strategies. The highest fuel consumption has an operating point at 6-bar BMEP with EGR system compared with the two other operating points.

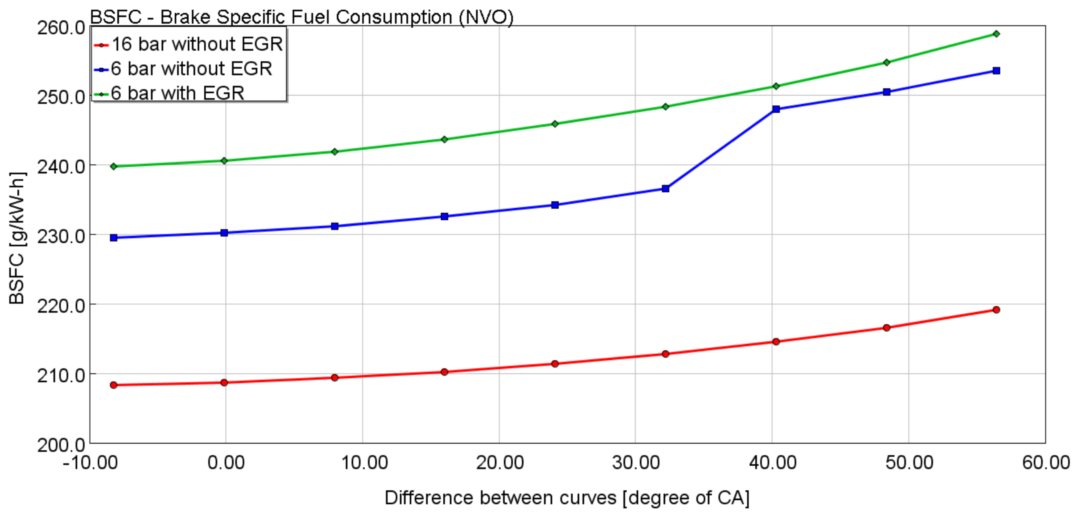


Figure 19 – BSFC (NVO)

Table 8 shows BSFC of all NVO strategies.

BSFC [g/kW.h]			
IVO and EVC difference [deg] of CA	**BMEP**		
	16 bar without EGR	6 bar with EGR	6 bar without EGR
-8,2	208,3	239,6	229,5
-0,1	208,6	240,5	230,1
7,9	209,3	241,8	231,2
16,0	210,2	243,6	232,6
24,1	211,4	245,8	234,1
32,2	212,8	248,3	236,5
40,3	214,5	251,2	247,9
48,4	216,6	254,7	250,4
56,5	219,1	258,8	253,4

Table 8 – BSFC (NVO)

The next parameter which was evaluated was the burned mass percentage at the SOC (Figure 20). The burned mass percentage at the SOC indicates how much of the warm mass of burned gases remain in the cylinder, unscavenged.

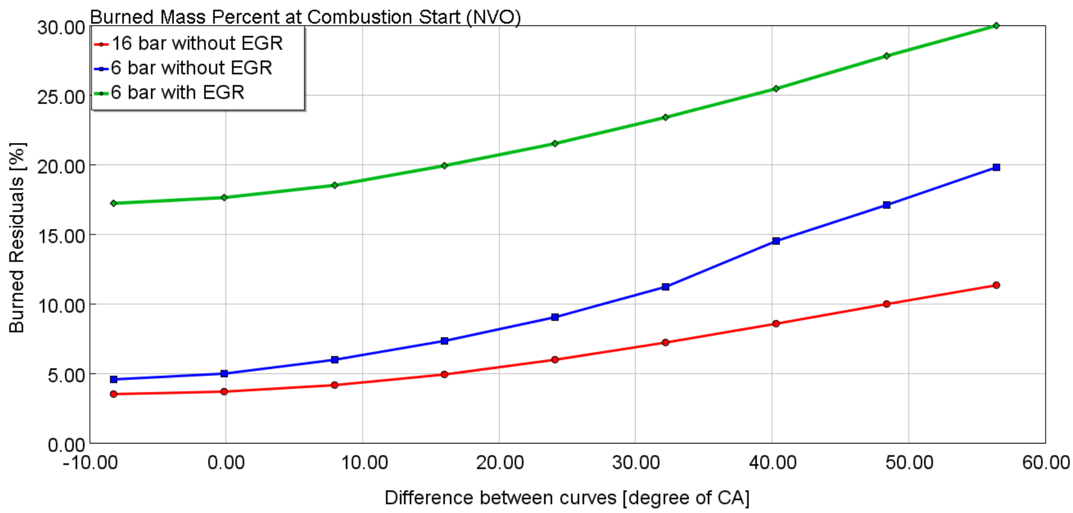


Figure 20 - Burned mass percent at combustion start (NVO)

Table 9 shows the burned mass percentage at the SOC of all NVO strategies. The lowest amount of mass in the cylinder was at the operating point of 16-bar BMEP. The highest amount of mass in the cylinder was at the operating point of 6-bar BMEP with EGR system.

Burned mass percent at combustion start [%]			
IVO and EVC difference [deg] of CA	BMEP		
	16 bar without EGR	6 bar with EGR	6 bar without EGR
-8,2	3,5	17,2	4,5
-0,1	3,7	17,6	5,0
7,9	4,1	18,5	6,0
16,0	4,9	19,9	7,3
24,1	6,0	21,5	9,1
32,2	7,2	23,4	11,2
40,3	8,6	25,4	14,5
48,4	10,0	27,8	17,1
56,5	11,4	30,0	19,7

Table 9 - Burned mass percent at combustion start (NVO)

7.3. Transient state – early exhaust valve opening EEVO

In this chapter the transient state of the EEVO strategy was simulated. The initial temperature was set at -7 °C because of standardized aftertreatment tests (for more information look at reference [13]). The operating point of the EEVO strategy was set on 2000 RPM. The model was simulated with 16-bar BMEP and 6-bar BMEP. The EGR system was turned off. The simulated curves were identical to those in the steady state simulations.

The diesel oxidation catalyst had a "light-off" temperature of 200 °C. The aim of transient state was to determine which EEVO strategy could heat-up the aftertreatment in the shortest amount of time.

Figure 21 shows the temperature of the DOC for all the EEVO strategies dependent on varying times. The detail of 200 °C is in Figure 22.

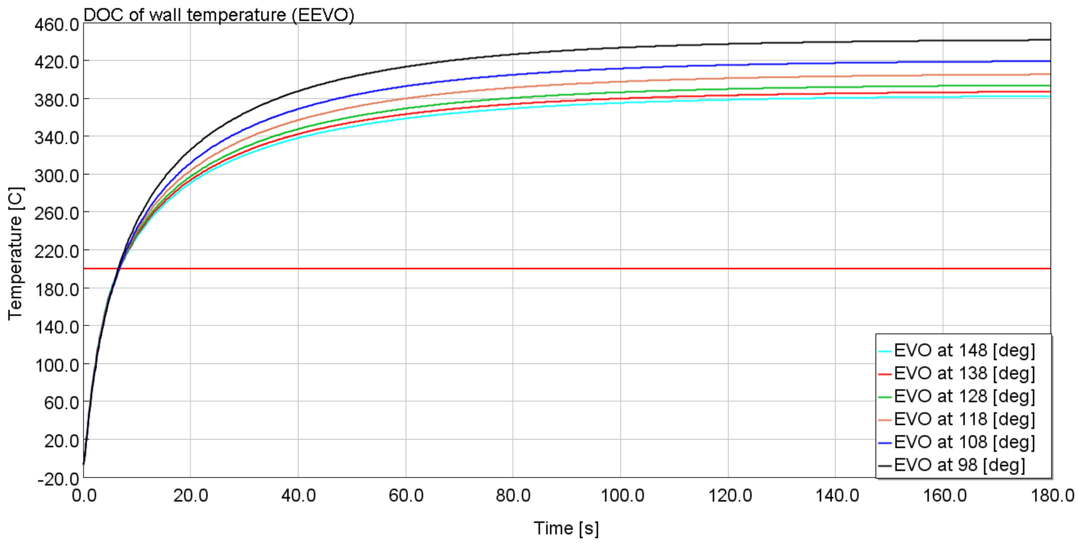


Figure 21 – Wall Temperature of DOC (EEVO) – 16 bar BMEP

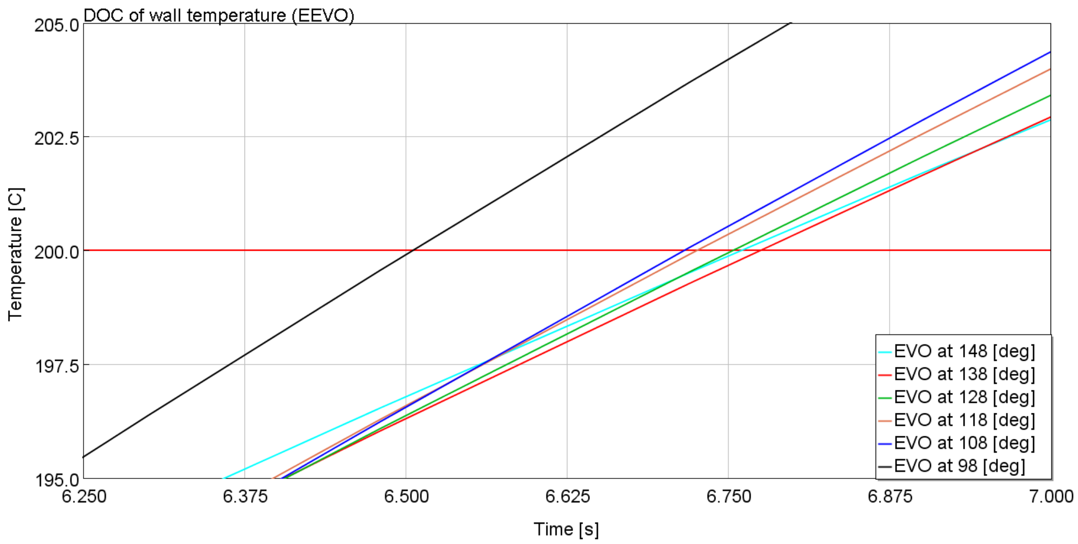


Figure 22 - Detail of wall temperature of DOC – 16 bar BMEP

In Figure 22 the purple curve, which starts opening a 98-degree CA, has the fastest aftertreatment heat-up time. While the interval of opening the exhaust valve is linear, the curves in figure are not because of different flow in the turbine.

Figure 23 shows all the EEVO strategies depending on time, with the operating point of 6-bar BMEP. The EGR system is turned off. The detail of 200 °C is in Figure 24.

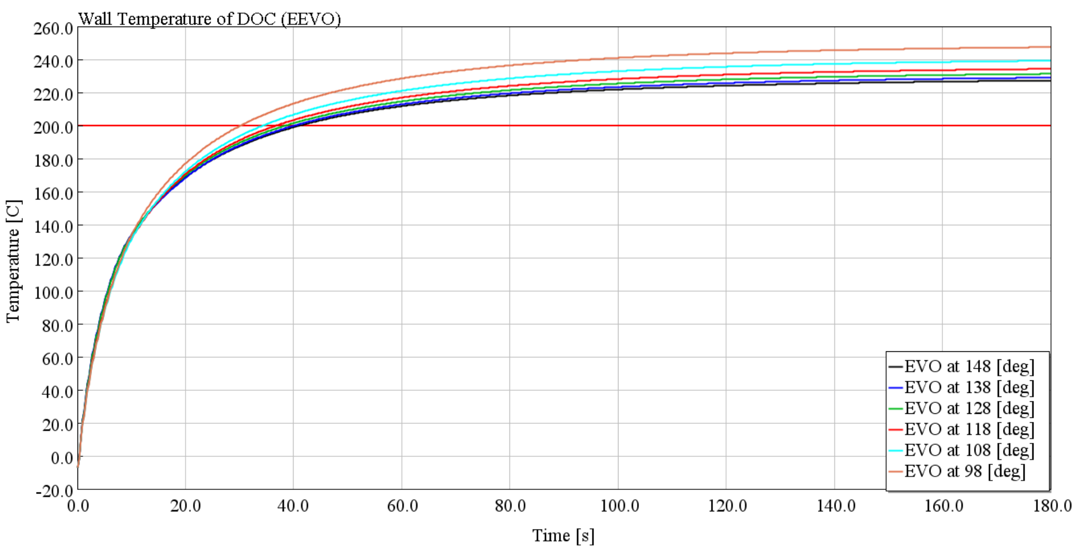


Figure 23 - Wall temperature of DOC (EEVO) - 6 bar BMEP

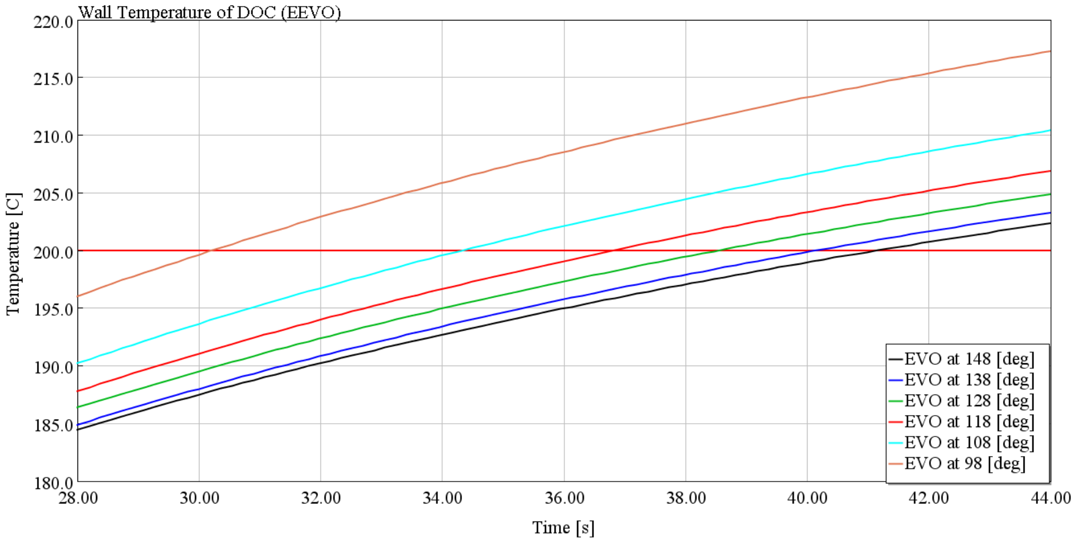


Figure 24 - Detail of wall temperature of DOC (EEVO) - 6 bar BMEP

Figure 24 shows all the NVO strategies depending on time. The purple curve (EVO at a 98-degree CA) has the fastest aftertreatment heat-up time.

Table 10 shows the times of all EEVO strategies at 200 °C. The aftertreatment is heated fastest when the EVO starts at a 98-degree CA at the operating point of 16-bar BMEP.

Time [s]		
EVO [deg] of CA	**BMEP**	
	16 bar	**6 bar**
148	6,82	41,16
138	6,79	40,26
128	6,78	38,64
118	6,75	36,84
108	6,72	34,32
98	6,50	30,18

Table 10 - Time and temperature of 200 degree of Celsius (EEVO)

7.4. Transient state – negative valve overlap NVO

In this chapter the transient state of the NVO strategy was simulated. The initial temperature was set at -7 °C because of standardized aftertreatment tests (for more information look at page [13][6]). The operating point of the NVO strategy in the model was set at 2000 RPM. The model was simulated with 16-bar BMEP and 6-bar BMEP. The EGR system was turned off. The simulated curves were indetical to those in the steady state simulations.

The diesel oxidation catalyst had a "light-off" temperature of 200 °C. The aim of transient state was to ascertain which EEVO strategy had the shortest aftertreament heat-up time.

Figure 25 shows the temperature of DOC for all the NVO strategies, depending on time, at the operating point of 16-bar BMEP. 200 °C is marked with red line. Figure 26 shows the detail of 200 °C.

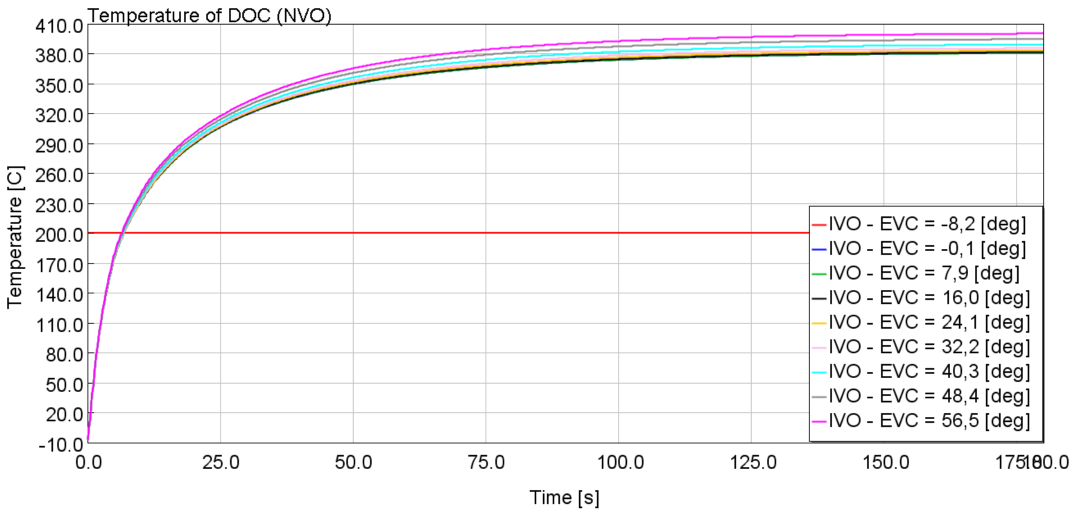


Figure 25 – Temperature of DOC (NVO) – 16 bar BMEP

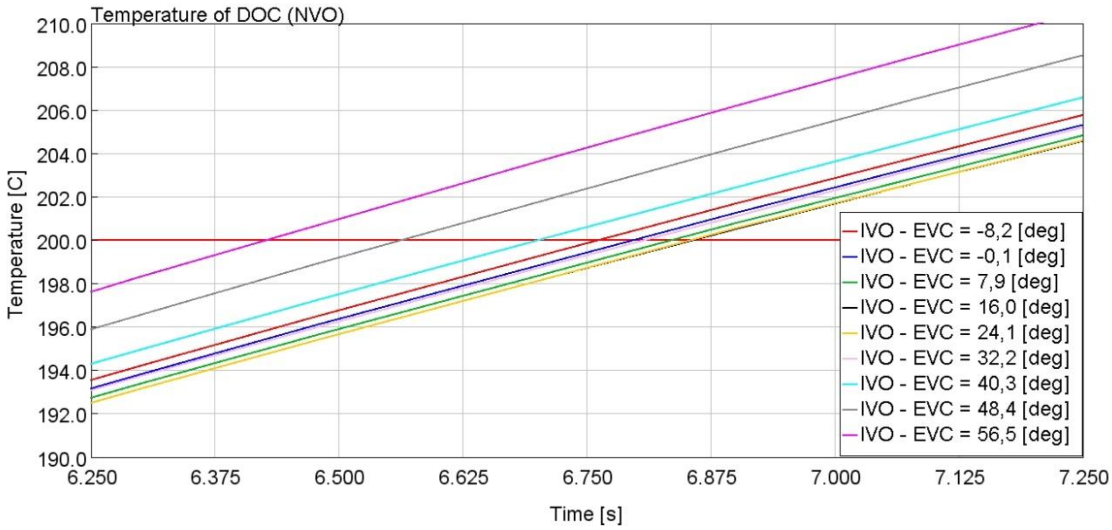


Figure 26 - Detail of temperature of DOC (NVO) – 16 bar BMEP

Figure 26 shows the detail of the wall temperature in all the NVO strategies. The pink curve represents the fastest aftertreatment heat-up time, with a difference of 56.5 degrees of CA between the IVO and the EVC.

Figure 27 shows all the NVO strategies with an operating point of 6-bar BMEP. The EGR system was turned off. 200 °C is marked with red line. Figure 28 shows the detail of all the NVO strategies.

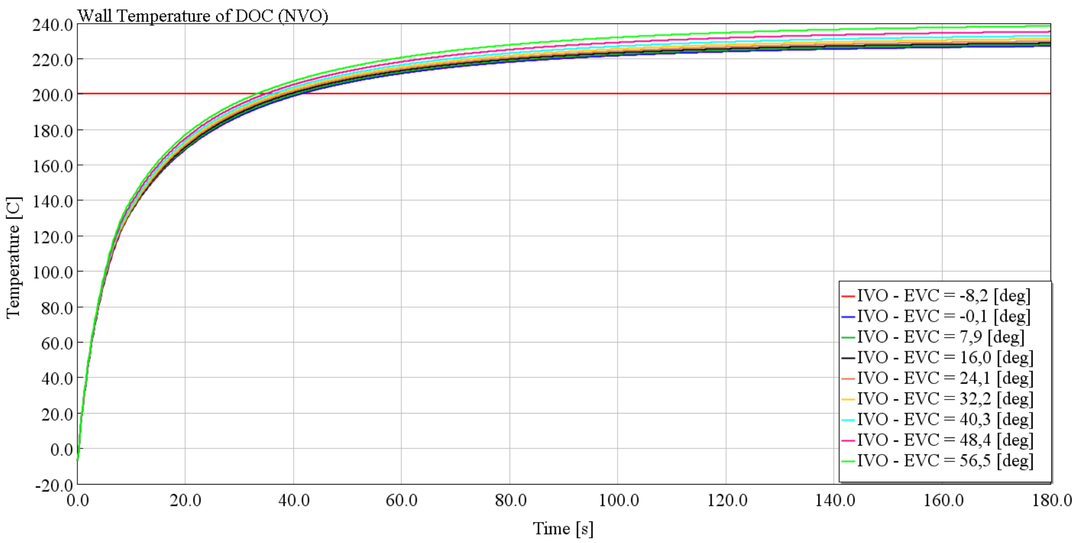


Figure 27 - Wall temperature of DOC (NVO) - 6 bar BMEP

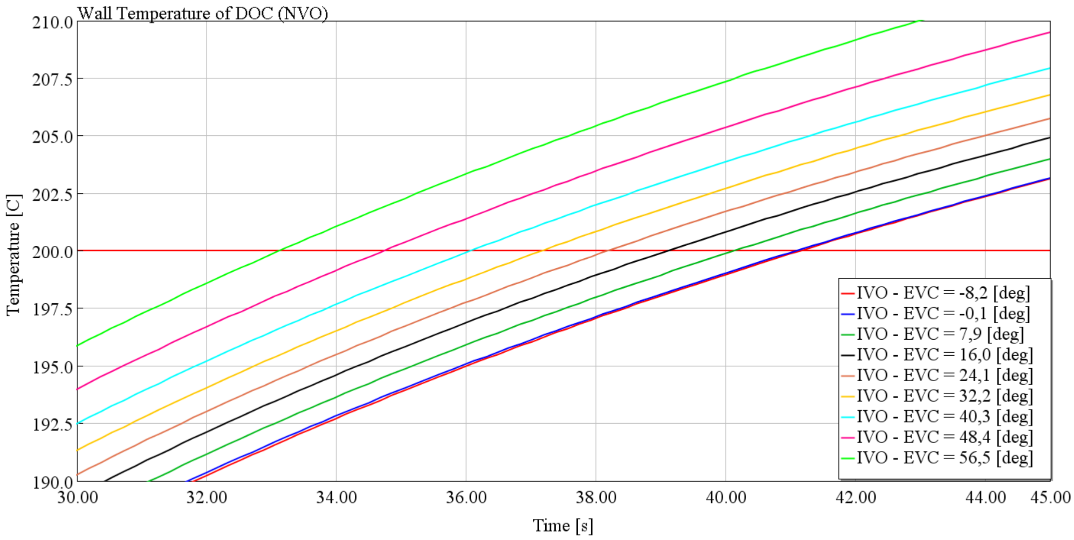


Figure 28 - Detail of wall temperature of DOC (NVO) - 6 bar BMEP

Figure 28 shows the detail of the wall temperature of the DOC of all the NVO strategies. The green curve represents the fastest aftertreatment heat-up, with a difference of 56.5 degrees of CA between the IVO and the EVC.

Table 11 shows the times of all the NVO strategies at 200 °C. The fastest aftertreatment heat-up time is when the difference between the IVO and the EVC is at a 56.5-degrees CA.

Time [s]		
IVO – EVC [deg] of CA	**BMEP**	
	16 bar	**6bar**
-8,2	6,72	41,17
-0,1	6,80	41,16
7,9	6,84	40,08
16,0	6,86	39,00
24,1	6,86	38,10
32,2	6,81	37,20
40,3	6,71	36,10
48,4	6,58	34,68
56,5	6,42	33,06

Table 11 - Time and temperature of 250 degree of Celsius (NVO)

7.5. Conclusions and next steps

The aim of this thesis was to ascertain the most efficient strategy for aftertreatment heat-up. The optimal strategy should have the shortest aftertreatment heat-up time with the lowest BSFC.

Figure 29, Figure 30, Figure 30and Figure 31 show the EEVO and NVO strategies with an operating point of 16-bar BMEP.

Figure 29 shows BSFC increase to base line. The NVO increases the BSFC by approximately 5.18 percent compared to the base line. The NVO strategy has a lower BSFC than the EEVO strategy.

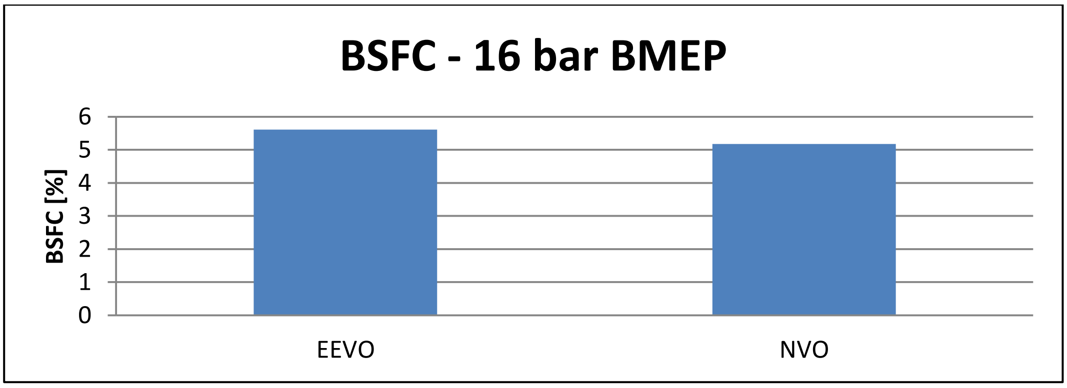


Figure 29 - BSFC - 16 bar BMEP

Figure 30 shows the time of how long it takes the aftertreatment to heat up to 200 °C. 200 °C is the "light-off" temperature of the DOC. Based on these results, the NVO strategy has a lower BSFC and a shorter heat-up time.

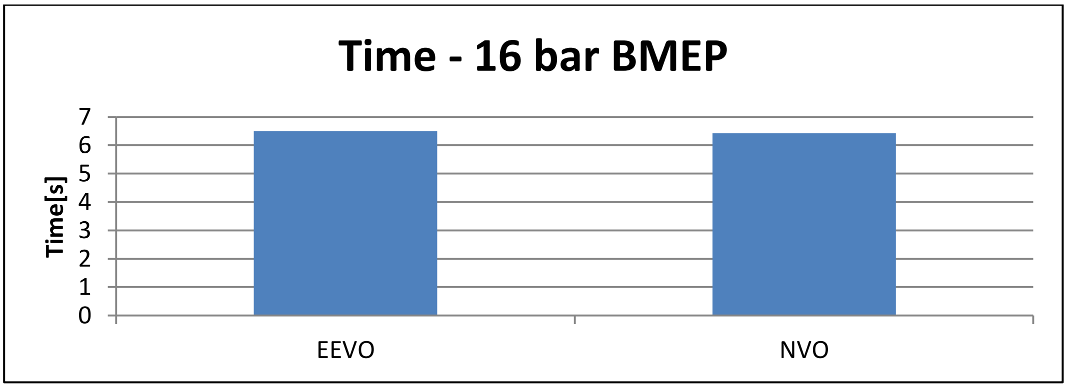


Figure 30 – Time - 16 bar BMEP

Figure 31 shows the DOC wall temperature increase compared to the base line. The NVO strategy heats up the aftertreatment at a higher temperature than the EEVO strategy. The NVO temperature has a 23.11% increase compared to the base line.

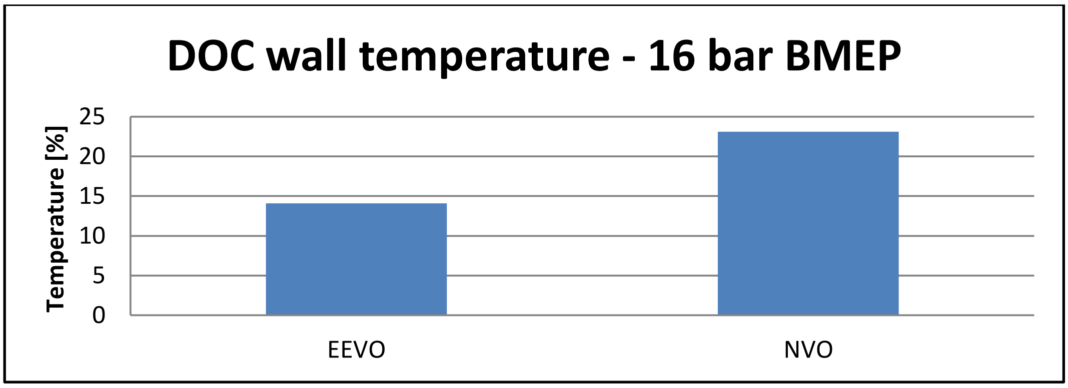


Figure 31 – DOC wall temperature - 16 bar BMEP

Figure 32, Figure 33 and Figure 34 show the EEVO and NVO strategies with the operating point of 6-bar BMEP.

Figure 32 shows the BSFC increase to the base line. The EEVO increases the BSFC by approximately 6.19% compared to the base line. The EEVO strategy has a lower BSFC than the NVO strategy

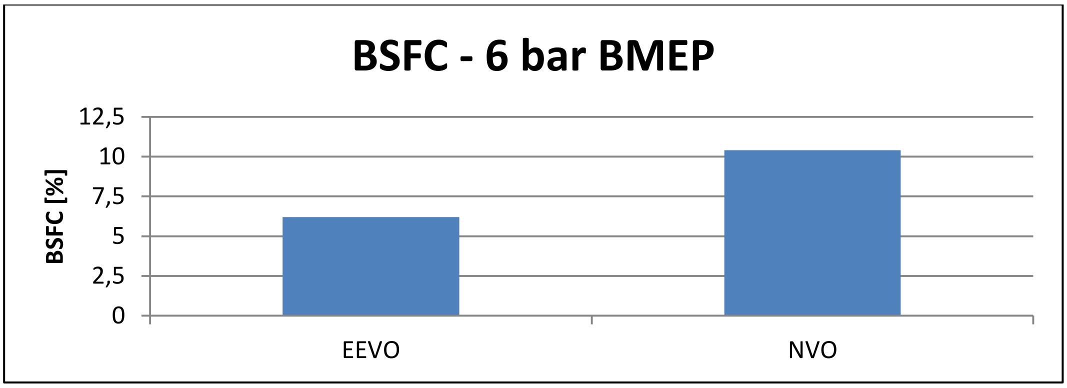


Figure 32 - BSFC - 6 bar BMEP

Figure 33 shows the time of how long it takes the aftertreatment to heat up to 200 °C. 200 °C is "light-off" temperature of the DOC. Based on these results, the EEVO strategy has a lower BSFC and a shorter heat-up time.

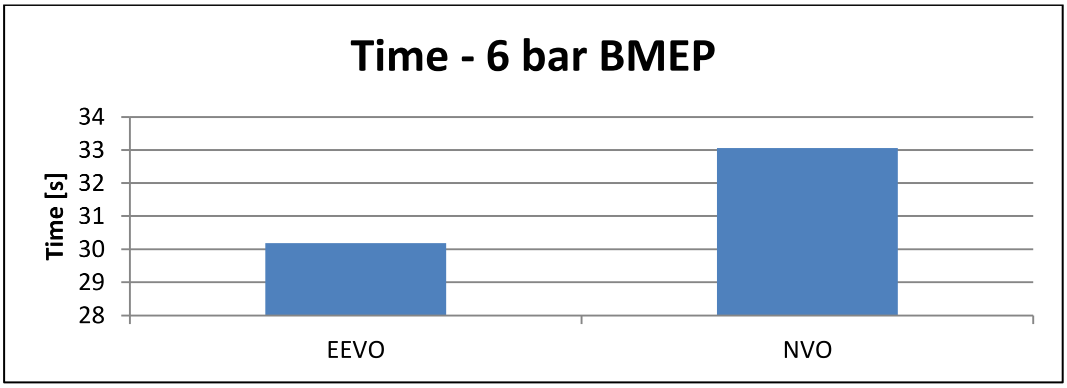


Figure 33 –Time 6 bar BMEP

Figure 34 shows the DOC wall temperature increase compared to the base line. The NVO strategy heats up the aftertreatment at a higher temperature than the EEVO strategy. The NVO temperature increase is by 30.23% compared to the base line.

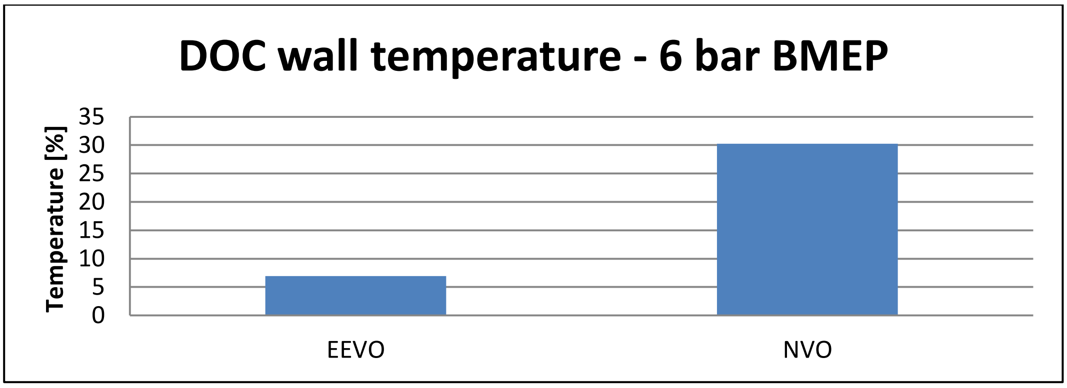


Figure 34 - Temperature - 6 bar BMEP

The optimum strategy for quick aftertreatment heat-up is the NVO strategy in higher loads (16-bar BMEP). The NVO strategy is able to heat up the aftertreatment to the "light-off" temperature after 6.42 seconds. The EEVO strategy is the best solution for lower loads (6-bar BMEP). It has a lower BSFC and a shorter heat-up time of 30.18 seconds.

Future studies could examine the simulations of both strategies in the driving cycles (NEDC, WLTC). Once the simulations of the driving cycles will be completed, the amount of emissions would be compared with the Euro emissions standards. If the emissions will pass the Euro emissions standards, the next step could be to design a cam shaft and do the experiment on a real engine in a test cell.

8. References

[1] GSCHEIDLE, Rolf. *Příručka pro automechanika*. 3., přeprac. vyd. Praha: Europa-Sobotáles, 2007. ISBN 978-80-86706-17-7.

[2] STADLBAUER, Stephan, Harald WASCHL, Alexander SCHILLING a Luigi DEL RE. *DOC Temperature Control for Low Temperature Operating Ranges with Post and Main Injection Actuation* [online]. In: . 2013-04-08, s. - [cit. 2019-02-20]. DOI: 10.4271/2013-01-1580. Available from: http://papers.sae.org/2013-01-1580/

[3] *Comparative Study on the Differences between the EU adn US Legislation on Emissions in the Automotive Sector* [online]. 2016 [cit. 2019-02-14]. ISBN 978-92-846-0330-5. Available from: http://www.europarl.europa.eu/RegData/etudes/STUD/2016/587331/IPOL_STU(2016)587331_EN.pdf

[4] GOSALA, Dheeraj B, Aswin K RAMESH, Cody M ALLEN, et al. Diesel engine aftertreatment warm-up through early exhaust valve opening and internal exhaust gas recirculation during idle operation. *International Journal of Engine Research*. 2017, **19**(7), 758-773. DOI: 10.1177/1468087417730240. ISSN 1468-0874. Available from: http://journals.sagepub.com/doi/10.1177/1468087417730240

[5] REŞITOĞLU, İbrahim Aslan, Kemal ALTINIŞIK a Ali KESKIN. The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. *Clean Technologies and Environmental Policy* [online]. 2015, **17**(1), 15-27 [cit. 2019-02-25]. DOI: 10.1007/s10098-014-0793-9. ISSN 1618-954X. Available from: http://link.springer.com/10.1007/s10098-014-0793-9

[6] User´s manual GT- POWER - Flow theory

[7] PANAIT, Mircea. How the Diesel Particulate Filter Works. In: *Autoevolution* [online]. 8 Jan 2015 [cit. 2019-02-20]. Available from: https://www.autoevolution.com/news/how-the-diesel-particulate-filter-works-90866.html#agal_0

[8] Global Diesel Oxidation Catalyst Market 2017 By Manufacturers - Evonik Industries AG, Vineeth Chemicals. In: *Open PR Worldwide Public Relations* [online]. 08-29-2017 [cit. 2019-02-20]. Available from: https://www.openpr.com/news/687815/Global-Diesel-Oxidation-Catalyst-Market-2017-By-Manufacturers-Evonik-Industries-AG-Vineeth-Chemicals.html

[9] [online]. In: . [cit. 2019-02-20]. Available from: https://www.citacepro.com/dokument/wHRRgxaTs0K3v7Py

[10] MACEK, Jan. *Spalovací motory I*. Praha: Nakladatelství ČVUT, 2007. ISBN 978-80-01-03618-1.

[11] EGR - Exhaust Gas Recirculation. *STT EMTEC emission and engine technology* [online]. [cit. 2019-02-27]. Available from: http://www.sttemtec.com/en/egr/egr.php

[12] OGAWA, Shigeru a Soma USUI. Heat Transfer Enhancement by Vortex Generators for Compact Heat Exchanger of Automobiles. *Open Journal of Fluid Dynamics* [online]. 2018, **08**(03), 321-330 [cit. 2019-04-03]. DOI: 10.4236/ojfd.2018.83020. ISSN 2165-3852. Available from: http://www.scirp.org/journal/doi.aspx?DOI=10.4236/ojfd.2018.83020

[13] Passenger cars and light duty vehicles. In: *Delphi Technologies* [online]. s. 126 [cit. 2019-04-09]. Available from: https://d2ou7ivda5raf2.cloudfront.net/sites/default/files/inline-files/booklet%20emission%20complete%20%20PC18.pdf